



The Influence of Nontidal Sea Level Height and Current Changes on the Earth's Rotation and Polar Motion During 1992-1994

by

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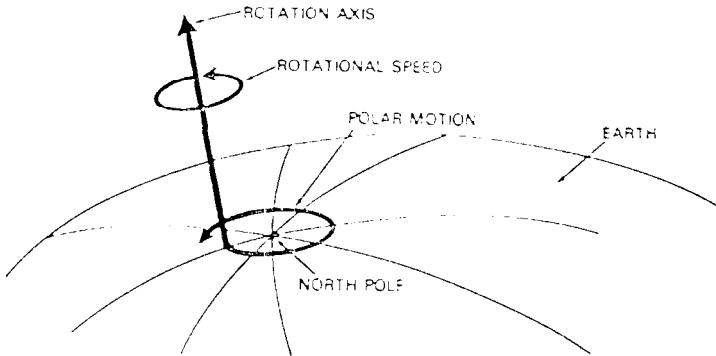
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Biarritz, France

- Use products of Ocean General Circulation Models (OGCMs) to evaluate effects of ocean current and bottom pressure changes on length-of-day and polar motion during 1992–1994
 - Princeton Modular Ocean Model (MOM)
 - Miami Isopycnal-Coordinate Ocean Model (MICOM)
- Compare model-predicted effects with observations of length-of-day and polar motion excitation
 - After removing atmospheric effects

VARIATIONS IN EARTH'S ROTATION

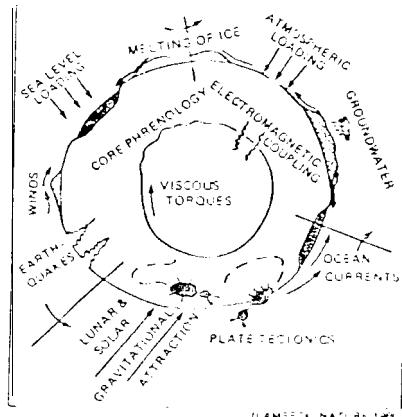


- POLAR MOTION: THE QUASI-PERIODIC, PROGRADE MOTION OF THE ROTATION AXIS AROUND THE NORTH POLE (scale ~ 10 meters)
- LENGTH-OF-DAY VARIATION: VARIATION IN THE ROTATIONAL SPEED. (-1 msec/day)

MILESTONE

- DYNAMICS BY EULER, 1752
- CHANDLER'S DISCOVERY OF POLAR MOTION, 1891.
- AST ROME TRIC OBSERVATION BY ILS (International Latitude Service) SINCE 1900
- ADVENT OF ATOMIC CLOCK IN 1950's
- NEW OBSERVATION TECHNIQUES SATELLITE DOPPLER, SATELLITE LASER RANGING, VERY-LONG-BASELINE INTERFEROMETRY SINCE 1970's.

POSSIBLE CAUSES:



- ATMOSPHERIC/OCEANIC CIRCULATION?
- SEISMIC ACTIVITIES?
- IMANTLE CONVECTION?
- CORE-MANTLE COUPLING?
- SOLAR ACTIVITIES?

SCIENTIFIC SIGNIFICANCE:

- TO IMPROVE UNDERSTANDING OF EARTH'S GLOBAL DYNAMICS
- INFERENCE FOR EARTH'S INTERIOR STRUCTURES

LONG PERIOD LIOUVILLE EQUATION

- Conservation of angular momentum expressed within rotating, body-fixed reference frame

$$\frac{\partial \mathbf{L}}{\partial t} + \boldsymbol{\omega} \times \mathbf{L} = \boldsymbol{\tau}$$

where the angular momentum vector $\mathbf{L} = \mathbf{I} \cdot \boldsymbol{\omega} + \mathbf{h}$

- Assume rotation is small perturbation from state of uniform rotation at rate Ω . Keeping terms to first order results in long period Liouville equation

$$\begin{aligned} \mathbf{m}(t) - \mathbf{t} \frac{i}{\sigma_{cw}} \frac{\partial \mathbf{m}}{\partial t} &= \psi(t) \\ &= \chi(t) - \frac{i}{\Omega} \frac{\partial \chi}{\partial t} \end{aligned}$$

where $\mathbf{m} = (\omega_1 + i \omega_2)/\Omega$ (terrestrial location of rotation pole)
 $\psi(t), \chi(t)$ are the polar motion excitation functions
 σ_{cw} is complex-valued frequency of Chandler wobble

- Written in terms of reported polar motion parameters $\mathbf{p}(t) = x_p(t) - i y_p(t)$

In the σ domain:

$$\begin{aligned} \mathbf{p}(t) + \frac{i}{\sigma_{cw}} \frac{\partial \mathbf{p}}{\partial t} &= \chi(t) \\ &= -\frac{1.61}{\Omega(C-A)} \left[\mathbf{h}(t) + \frac{\Omega \mathbf{c}(t)}{1.44} \right] \end{aligned}$$

if $C = A$, then

$$\mathbf{p}(\sigma) = \frac{\sigma_{cw}}{\sigma_{cw} - \sigma} \chi(\sigma)$$

OCEAN ANGULAR MOMENTUM (OAM)

- o Angular momentum of oceans changes due to:
 - rotation due to Earth's rotation
 - rotation due to ocean currents
- o "Conservative" changes of angular momentum due to rotation of the solid Earth
- o OAM can be computed from products of OGCMs by:

(from: <http://www.oceanum.vt.edu/~jewett/OGCMs/OGCM.html>)

$$\begin{aligned}
 M^P(t) &= M_1^P(t) + M_2^P(t) = \int_{V_o} r^2 \Omega \rho(r,t) \sin\phi \cos\lambda \cos\theta \sin\lambda \, dV \\
 M_3^P(t) &= \int_{V_o} r^2 \Omega \rho(r,t) \cos^2\phi \, dV \\
 M^c(t) &= M_1^c(t) - i M_2^c(t) = \int_{V_o} \rho(r,t) r \sin\phi n(\mathbf{r},t) + v(\mathbf{r},t) \cos\lambda \cos\theta \sin\lambda \, dV \\
 M_3^c(t) &= \int_{V_o} \rho(r,t) r \cos\phi n(\mathbf{r},t) \, dV
 \end{aligned}$$

- o OAM is related to Earth rotation excitation functions by:

$$\chi(t) = \chi_1(t) + i \chi_2(t) = \frac{1.61}{\Omega(C-A)} [M^c(t) + \frac{M^P(t)}{1.44}]$$

$$\Delta \Lambda(t) = \frac{\Lambda_o}{C_m \Omega} [M_3^c(t) + 0.756 M_3^P(t)]$$

ATMOSPHERIC ANGULAR MOMENTUM (AAM)

- Angular momentum of atmosphere changes due to:
 - rotation of Earth
 - atmospheric tides
 - atmospheric circulation changes
- Under principle of conservation of angular momentum, the rotation of the solid Earth changes as AAM is exchanged with the solid Earth
- AAM χ -functions quantify the atmospheric excitation of Earth's rotation

($\chi_1^P + i \chi_2^P = \chi_1^w + i \chi_2^w$)

$$\chi_1^P + i \chi_2^P = \frac{-1.00}{(C-A)g} a^4 \int p_s \sin\phi \cos^2\phi (\cos\lambda + i \sin\lambda) d\lambda d\phi$$

$$\chi_3^P(t) = \frac{0.70}{Cg} \int p_s \cos^3\phi d\lambda d\phi$$

(χ_3^P is a measure of atmospheric momentum)

$$\chi_1^w + i \chi_2^w = \frac{-1.43}{\Omega(C-A)g} a^3 \int (u \sin\phi \cos\phi + i v \cos\phi) (\cos\lambda + i \sin\lambda) dp d\lambda d\phi$$

$$\chi_3^w(t) = \frac{a^3}{C\Omega g} \int u \cos^2\phi dp d\lambda d\phi$$

- AAM χ -functions are computed from the operational analyses of the:
 - ENSO
 - JMA
 - NCEP
 - UKMO
- AAM χ -functions are computed from the reanalysis systems of the:
 - NCAR/NCEP/NOAA (DAS)
 - NCEP/NOAA

OCEANIC RESPONSE TO ATMOSPHERIC SURFACE PRESSURE FLUCTUATIONS

"How do oceans "communicate" atmospheric surface pressure fluctuations?"
ocean "bottom"

• oceanic response to atmospheric surface pressure fluctuations

"Topographic" communication

• oceanic response to atmospheric surface pressure fluctuations
• oceanic response to atmospheric surface pressure fluctuations
• oceanic response to atmospheric surface pressure fluctuations

"Hydrostatic" assumption

• oceanic response to atmospheric surface pressure fluctuations

• oceanic response to atmospheric surface pressure fluctuations

- ΔP_{atm} pressure terms computed under inverted barometer assumption
- ΔP_{atm} pressure terms available that have been computed under each of these assumptions

- ΔP_{atm} pressure terms computed under inverted barometer assumption chosen for use here

SPACE96 EARTH ORIENTATION SERIES

- A combination of space-geodetic Earth rotation measurements
 - IGS (International GPS service center)
 - GSFC (Goddard Space Flight Center for Space Research analysis center)
 - USNO (US Naval Observatory "High Tides" (both NOAA & USNC analyses), NASA, NOAA, GSFC, GSC) (National Space Geodesy Program & GSECI program for IGS and IGS analysis centers and IGS combined service)
- Individual series adjusted prior to their combination
 - Individual geodetic and tidal terms removed (when necessary) from UT1 values
 - Yoder *et al.* [1981] model used to remove effect of all long period solid Earth tides
 - Dickman [1993] model used to remove ocean tidal corrections to the Yoder *et al.* [1981] model values at the Mf , Mm , and Ssa tidal frequencies
 - Herring [1993] empirical model used to remove effect of semidiurnal and diurnal ocean tides on NOAA's IRIS "Intensive" UT1 values
- All data points of each series adjusted to be in agreement with each other
 - "Starting" uncertainties of each series adjusted so its residual with respect to a combination of all other series has a reduced chi-square of one
 - Outlying data points deleted
- Adjusted series combined using Kalman filter to form SPACE96
 - Consists of values for DMY, UT1-UTC, their formal uncertainties and correlations spanning September 23, 1976 to February 28, 1997 at daily intervals

SPACE96 EXCITATION FUNCTIONS

- o Signaling conditions for polar motion and UTTC
- o Kalman filter used to generate SPACE96
- o When generating SPACE96
- o Excitation functions used here are those estimated by Kalmans filter

APPROACH

- **Earth rotation observations**

Use SPACE96 Earth rotation excitation functions

- **SPACE96 is a Kalman filter-based combination of space-geodetic Earth rotation measurements**
- **Solid Earth and ocean tidal effects have been removed from Iod values**
- **Daily values at noon spanning 1976.8 -1997.1**

Form 3-day averages of daily noon values; demean and detrend

- **Remove effects of atmospheric wind and pressure**

Use the NCEP/NCAR reanalysis atmospheric angular momentum values

- **6-hour values spanning 1979–present**

- **Pressure term used is that computed assuming oceans respond as inverted barometer to imposed atmospheric pressure changes**

• Average over diurnal cycle by forming centered average of 5 successive values with weights 1/8, 1/4, 1/4, 1/4, 1/8

• Form 3-day average of daily noon values; demean and detrend

- **Compare residual to predictions of OGCM**

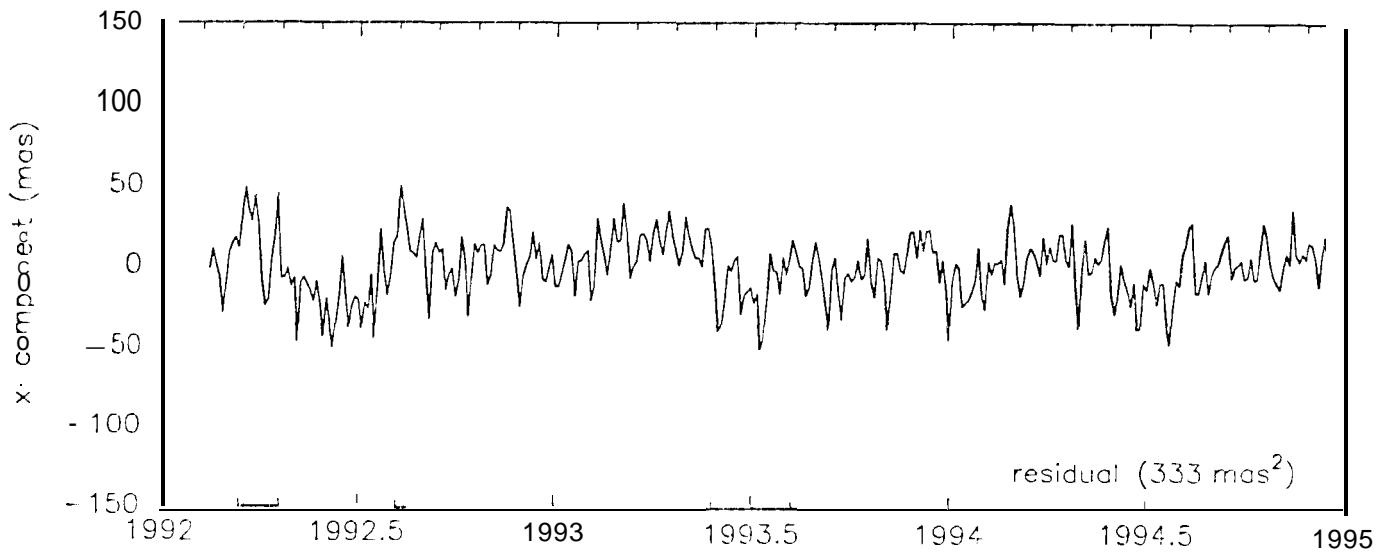
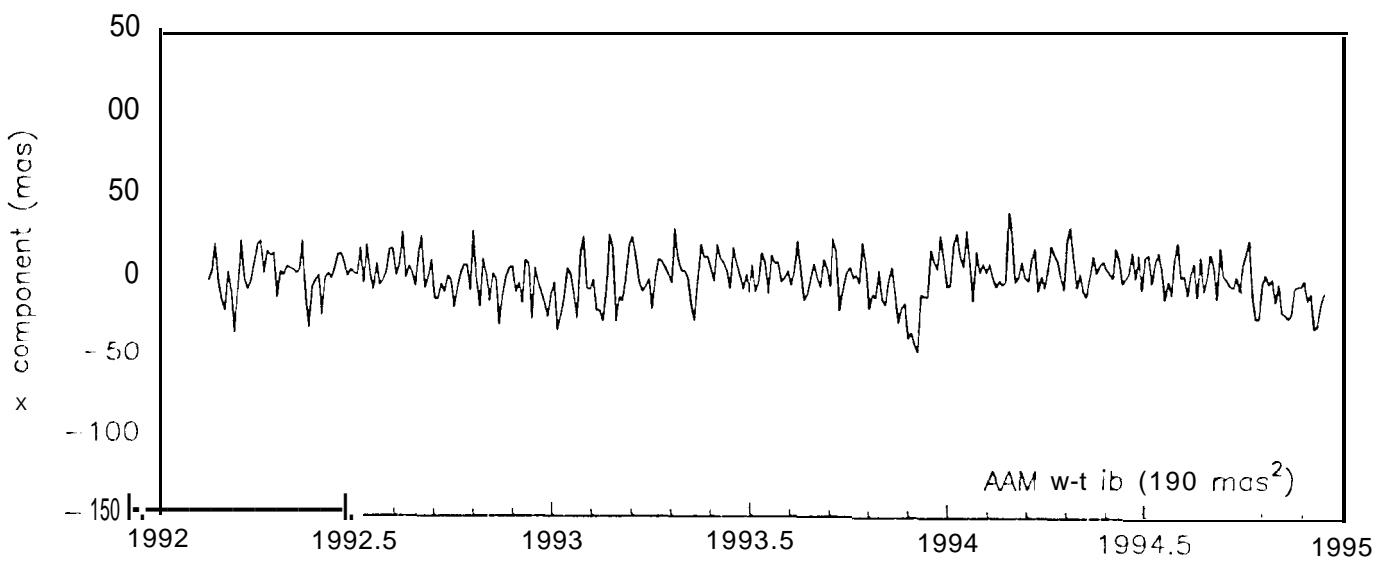
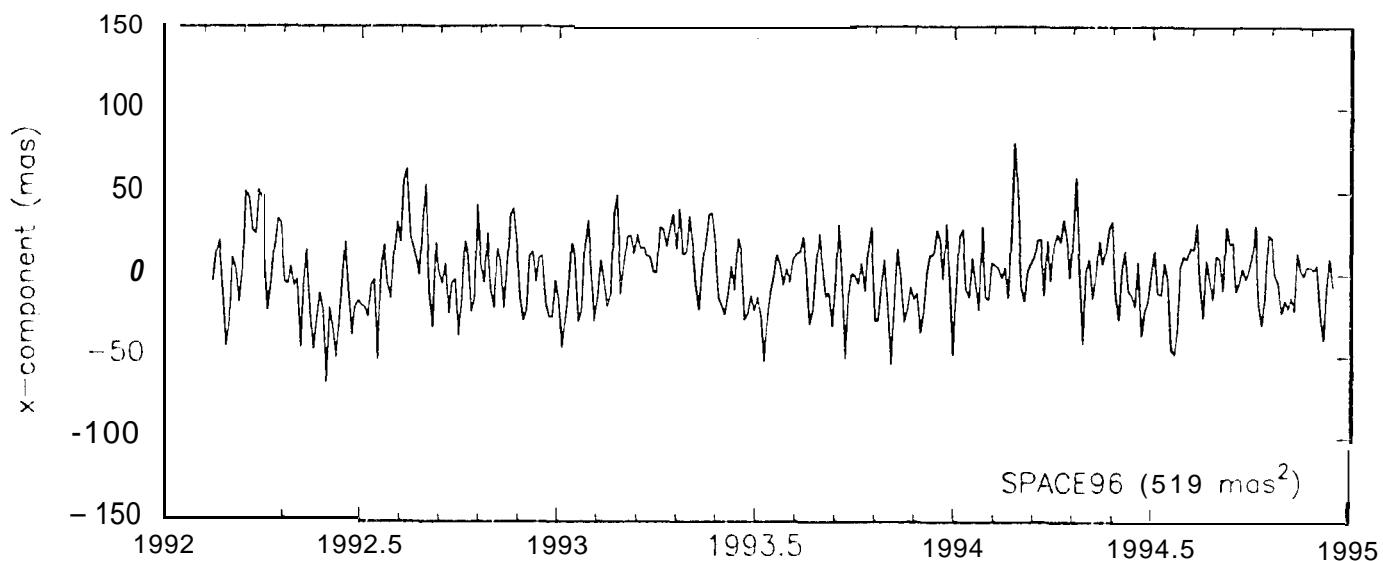
Use DAM values computed from AOMM and MIKCOM models run at JIS by Yi Chao

- **3-day averaged values at noon spanning 1992–1994**

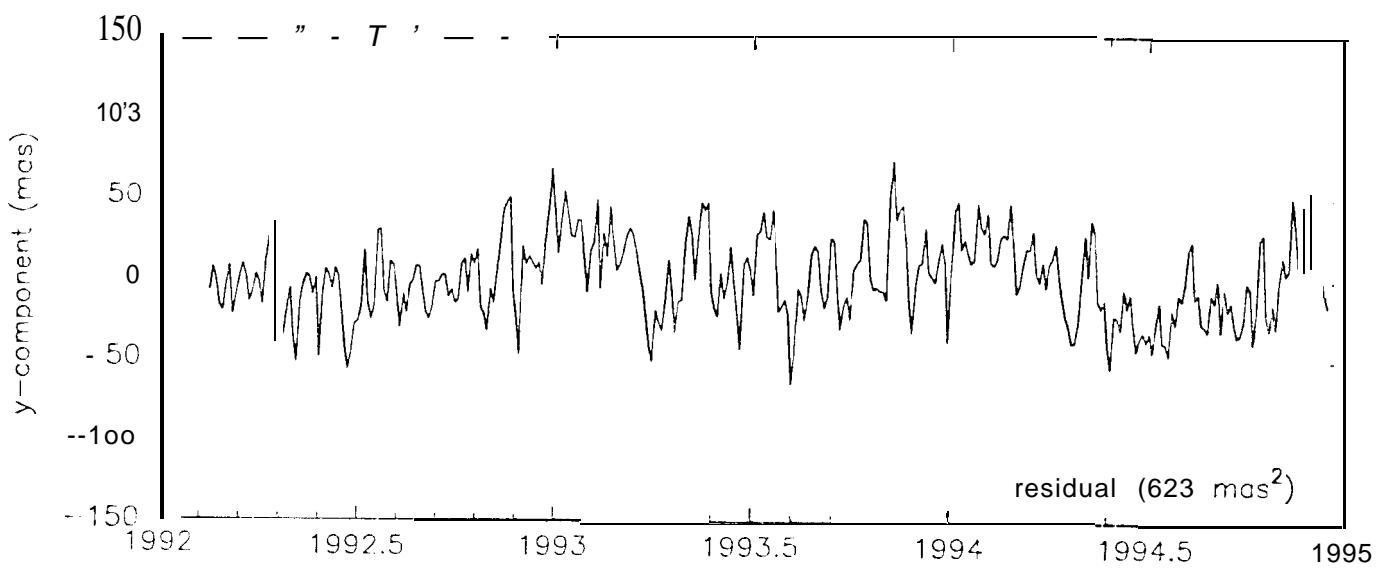
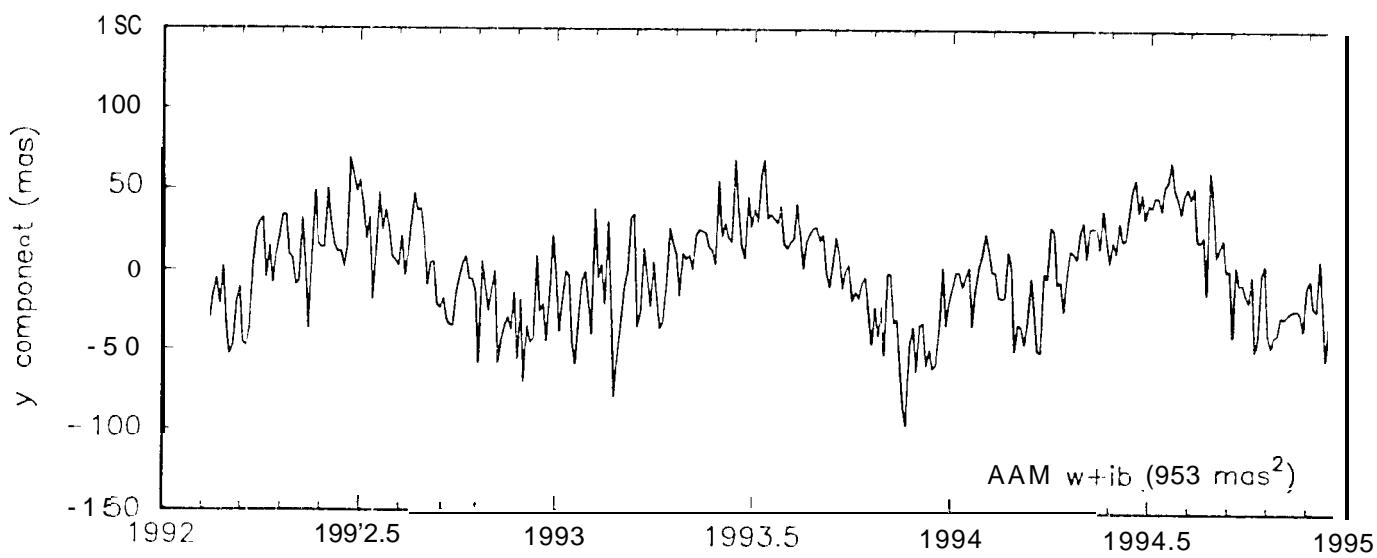
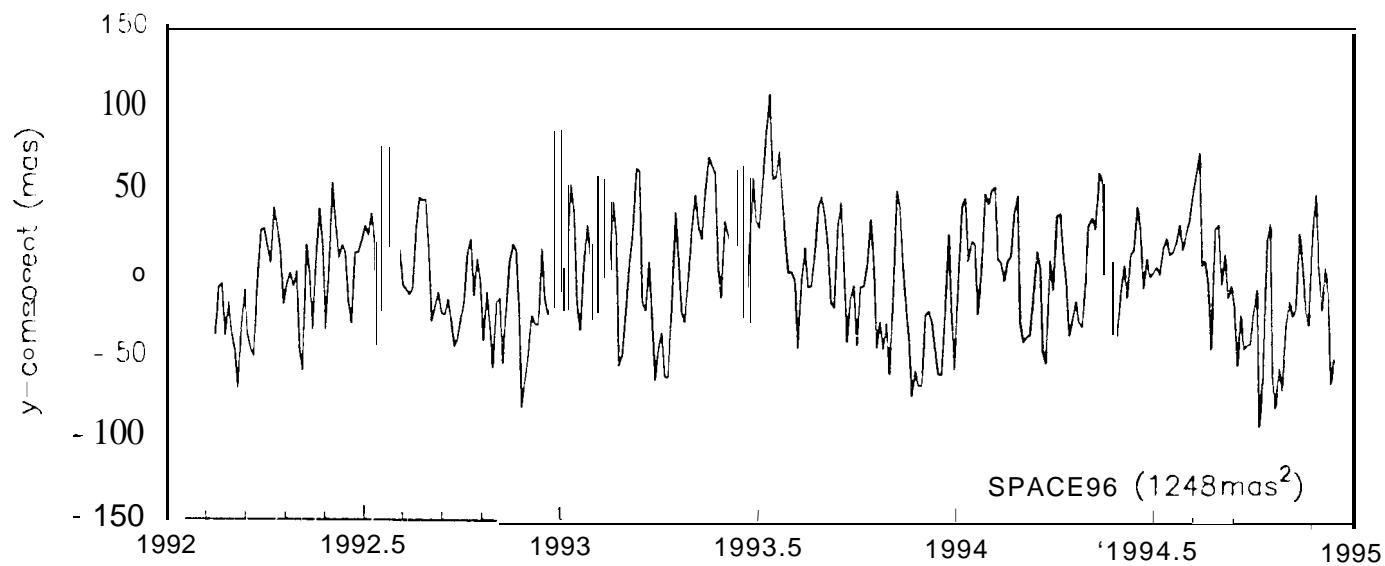
Convert to Earth rotation excitation functions

- **Correct model term for effects of mass non conservation**
- **Rebalance to account for in-situ tidal adjustment of model to climatological forcing**

POLAR MO ONE XCTA ON SERIES



POLAR MOTION EXCITATION SERIES



OCEAN MODELS

	Princeton MOM	Miami Isopycnal
Model domain	80°S to 80°N	80°S to 80°N
Horizontal resolution	2° long x 1° lat	2° long x 1° lat
Vertical layers	22	11 + mixed
Surface	rigid lid	free surface
Bottom topography	smoothed ETOPOS	smoothed ETOPOS
Model spinup	10 years with climatological air-sea fluxes	10 years with climatological air-sea fluxes
Forcing	daily NCEP winds and heat flux derived from bulk formula	daily NCEP winds, and heat flux derived from bulk formula
P – E	no	no
Simulation period	1992–1994	1992–1994
Output time resolution	6 day averages	3 day averages

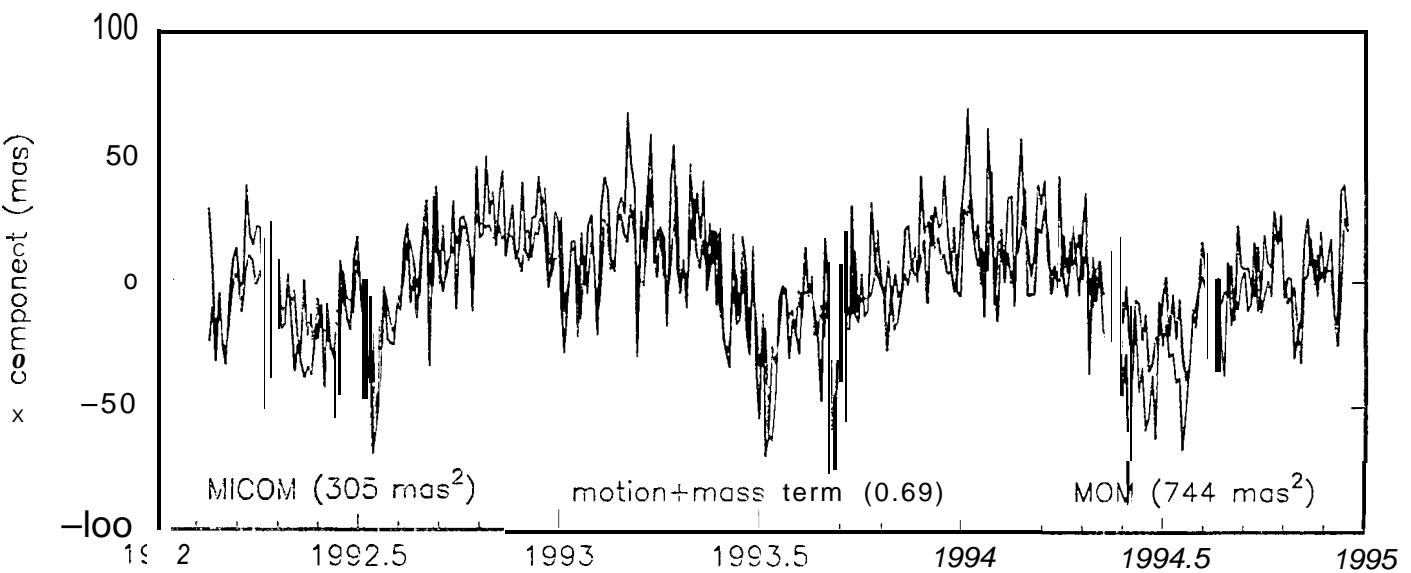
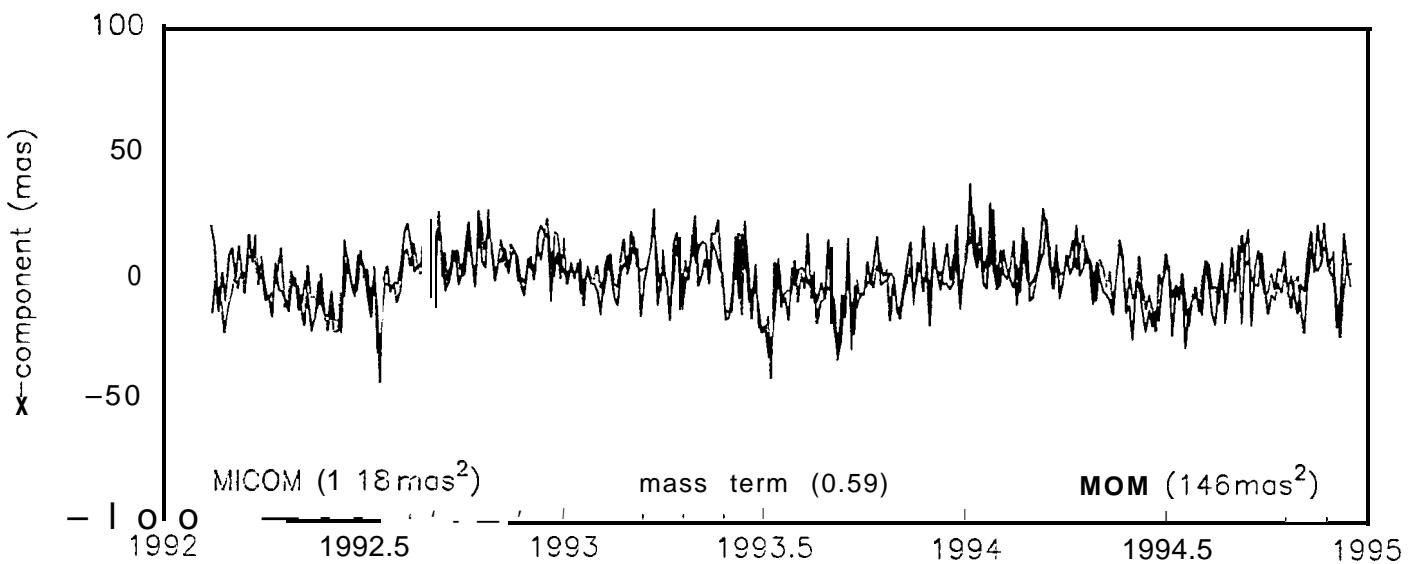
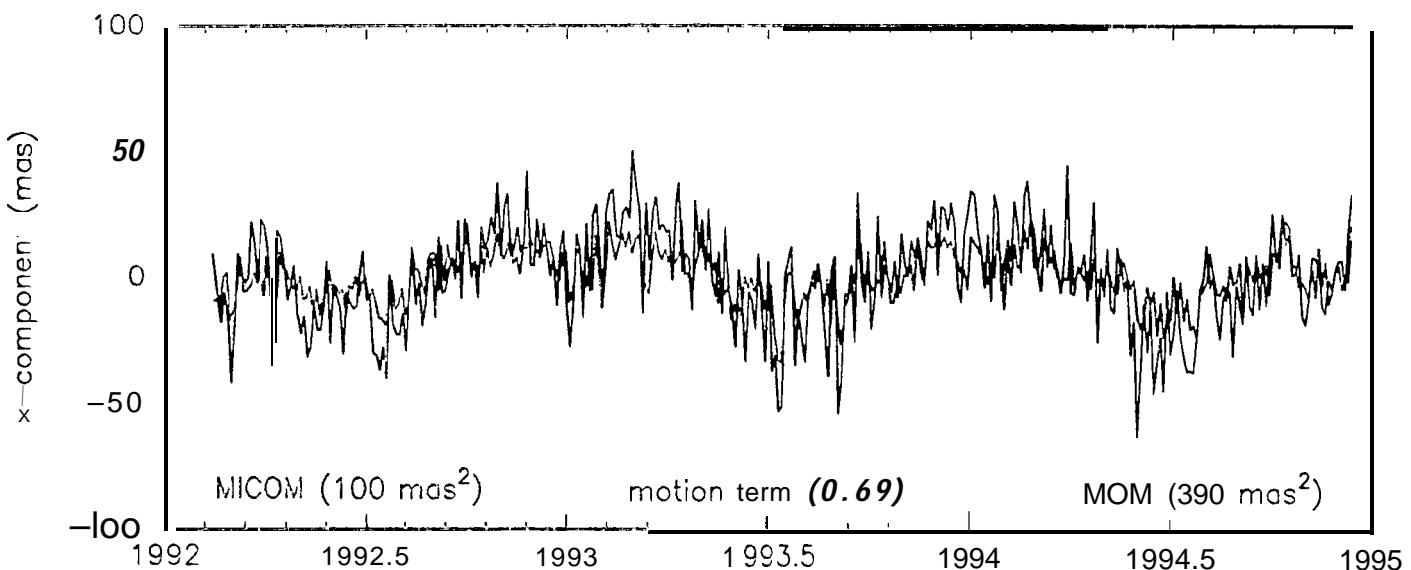
BOUSSINESQ MODELS

- The Boussinesq approximation is commonly used in ocean general circulation models (OGCMs)
 - Density variations in oceans are small
 - Usually less than $\pm 2.5\%$ of average density
 - Under Boussinesq approximation, density variations are ignored except in the gravitational buoyancy force
 - Density is not constant but changes as temperature, pressure, and salinity changes
- Boussinesq models conserve volume, not mass
 - Under Boussinesq approximation, conservation of mass equation $\nabla \cdot (\rho \mathbf{u}) = 0$ reduces to $\nabla \cdot \mathbf{u} = 0$ (conservation of volume)
- In Boussinesq ocean models, imposed heat flux can lead to model mass changes
 - Imposed heat flux \rightarrow temperature changes \rightarrow density changes via equation of state
 - Since model volume is constant, model mass must change to accommodate density change
 - Boussinesq models do not properly represent steric sea level, but can be corrected to do so (Greatbatch, 1994; Mellor & Ezer, 1995)
- Must account for mass non-conservation
 - Hence, we apply a factor designed to ensure mass conservation:

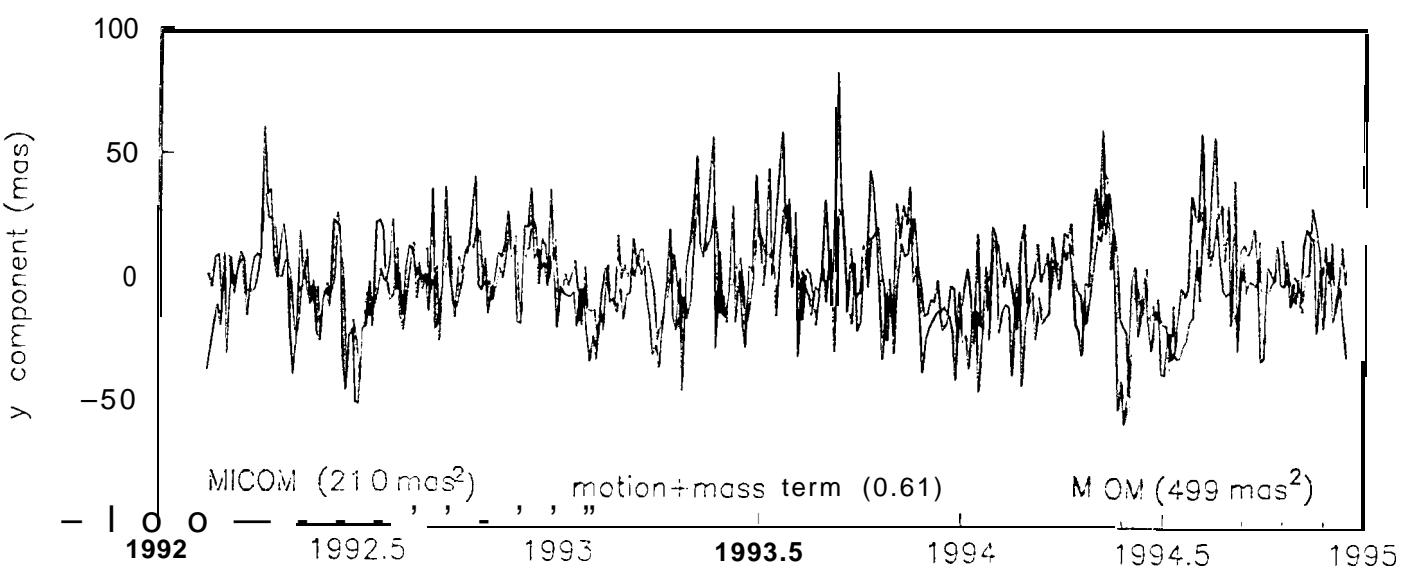
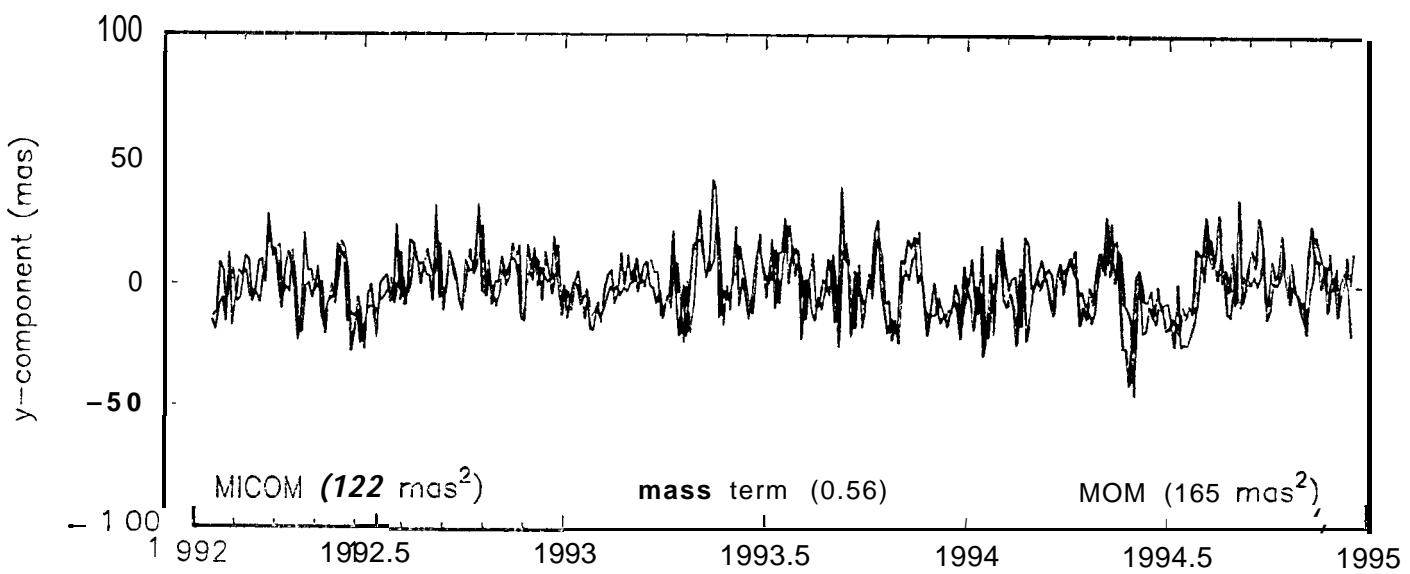
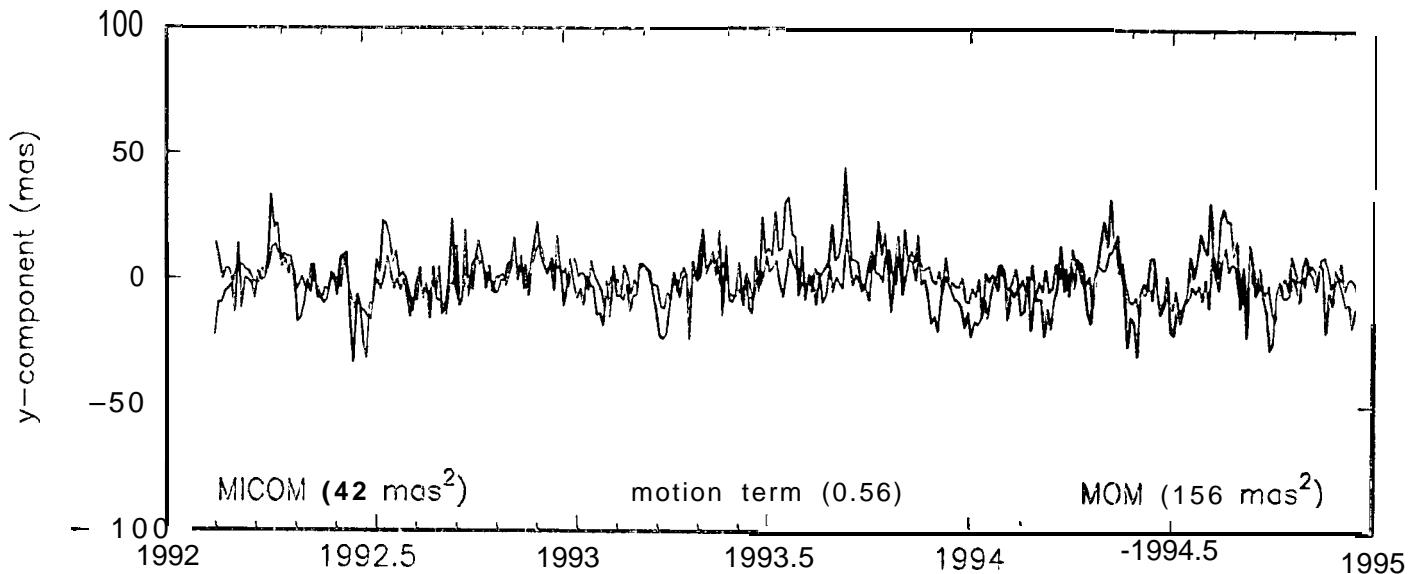
$$p^c(t) = p^u(t) + \Delta p(t) = p^u(t) + p^u(t) \frac{\Delta m(t)}{m(t)} = \frac{p^u(t)}{m(t)} \langle m \rangle$$

where: superscript c (u) denotes corrected (uncorrected) parameter $p(t)$,
 $\Delta p(t)$ is the correction applied, $m(t)$ is model mass at time t ,
 $\langle m \rangle$ is time-averaged model mass = $m(t) + \Delta m(t)$

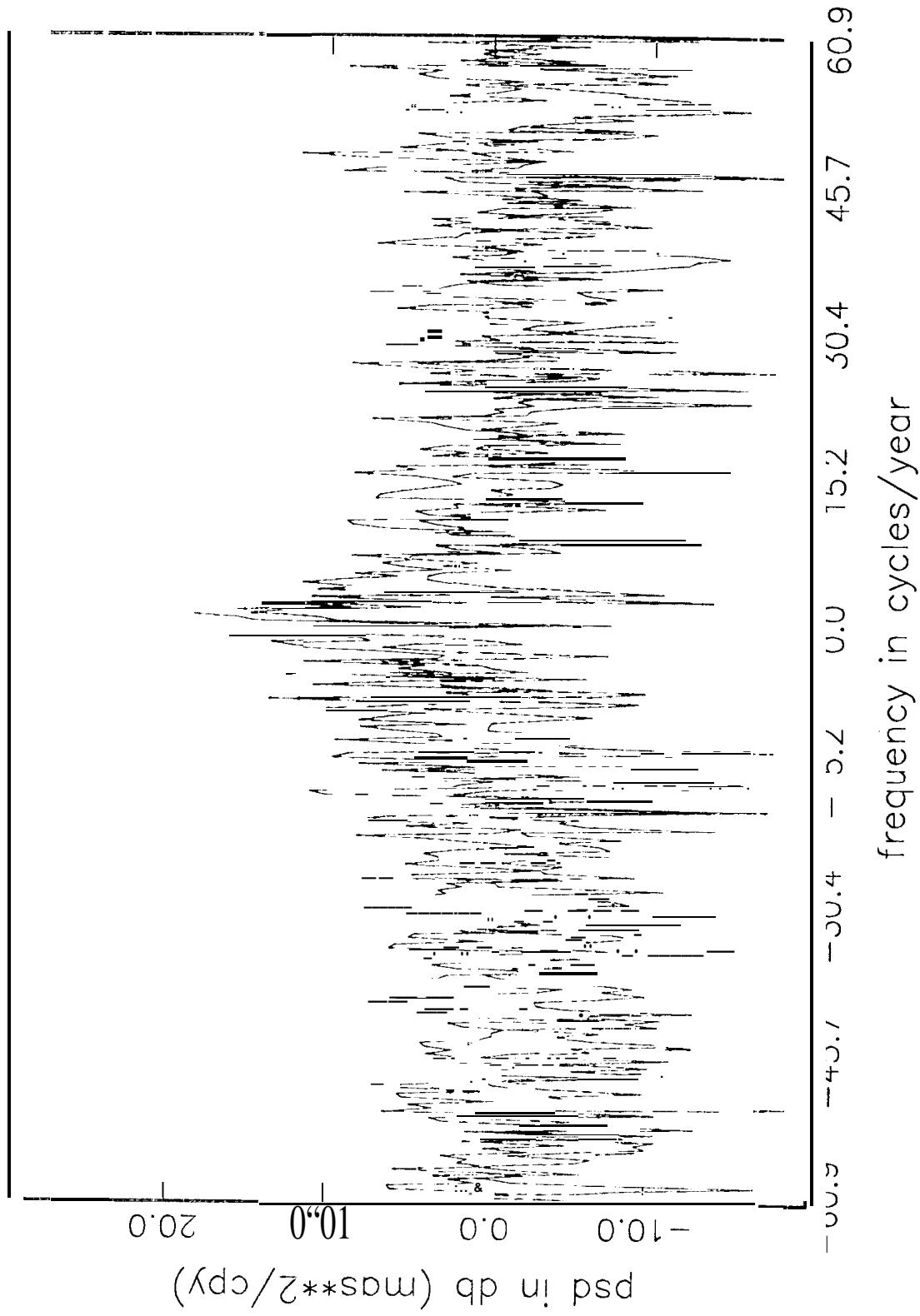
OCEAN C EXCITATION OF POLAR MOTION



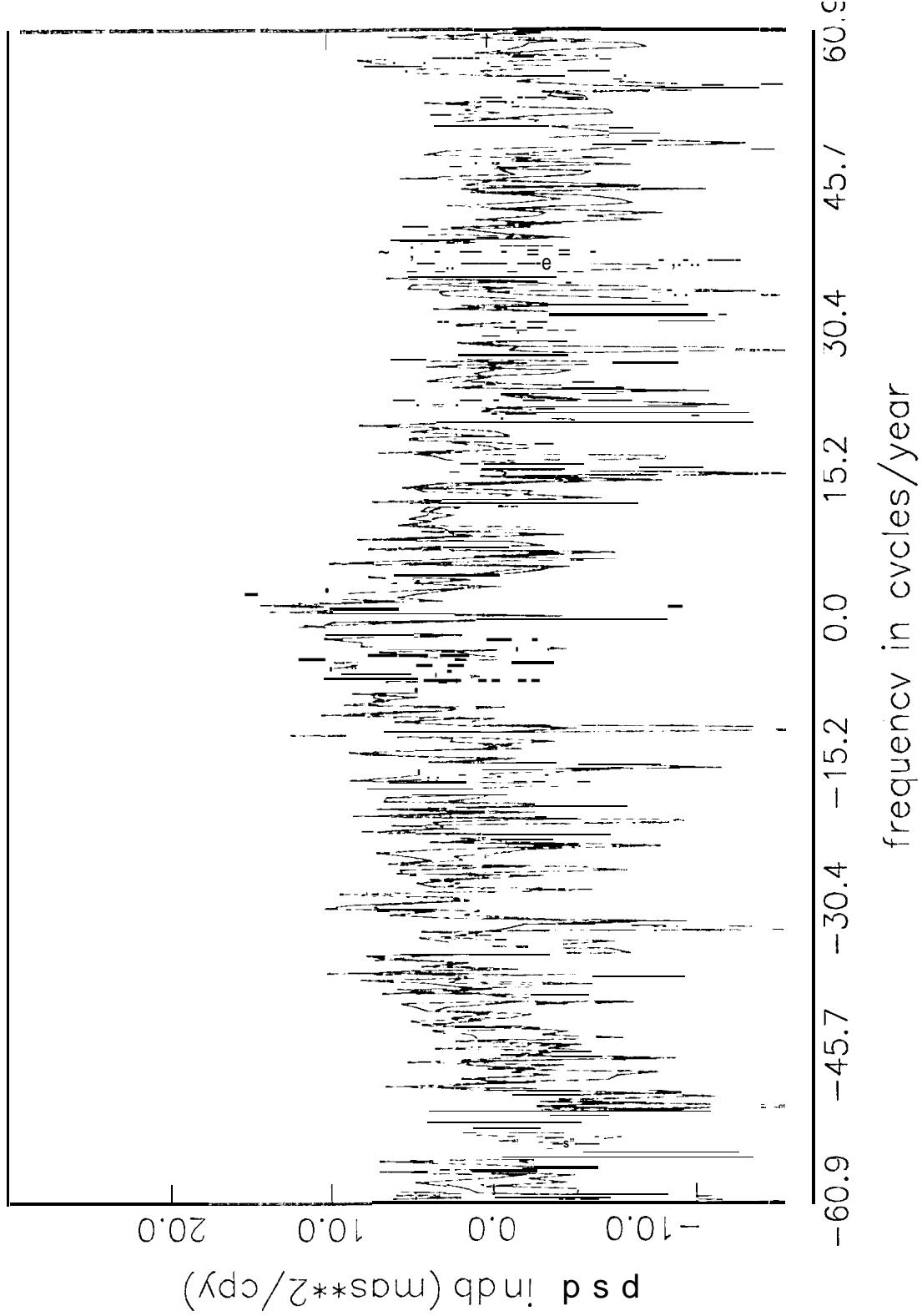
OCEANIC EXCITATION OF POLAR MOTION



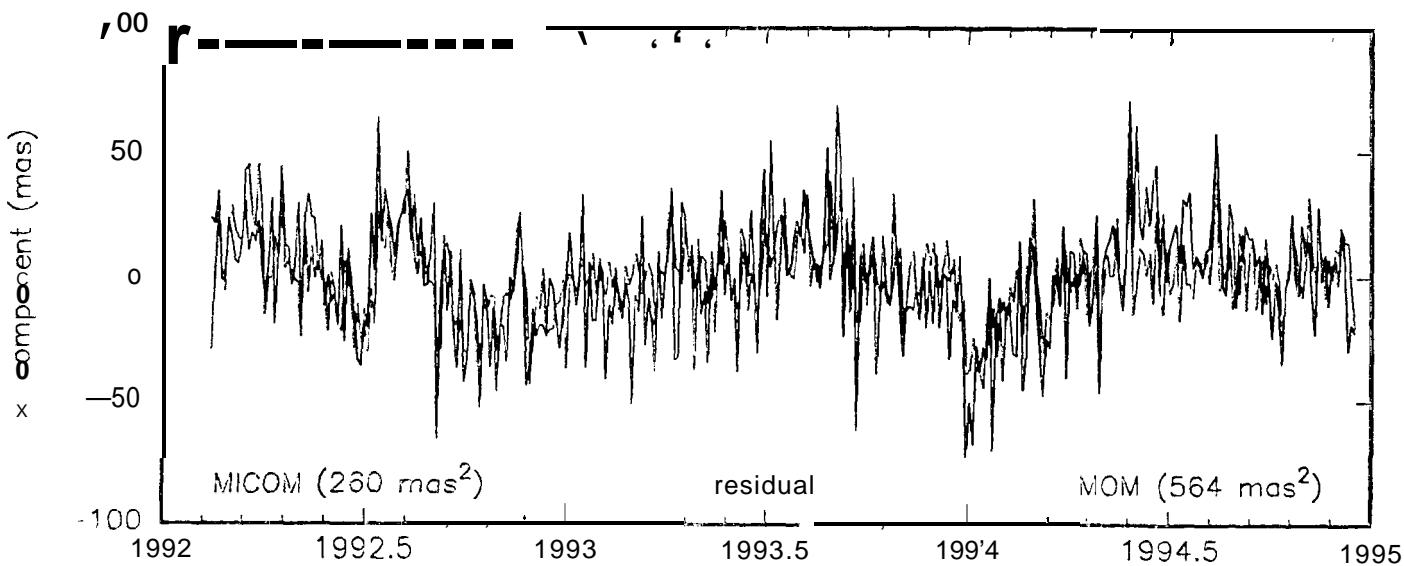
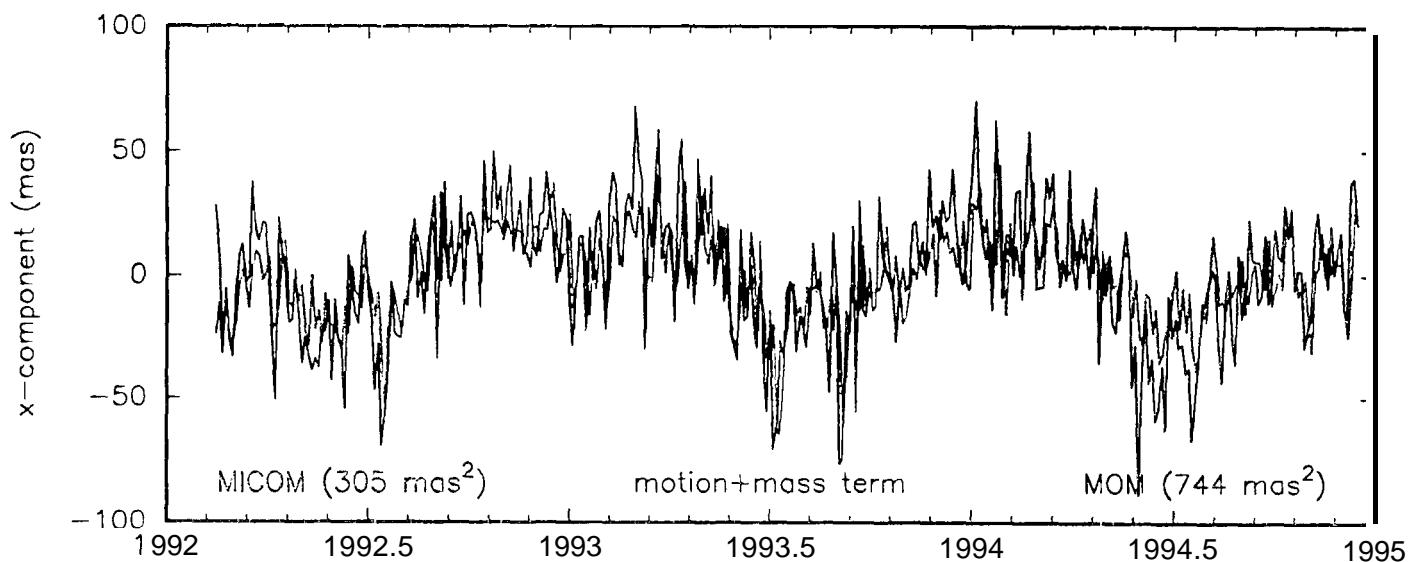
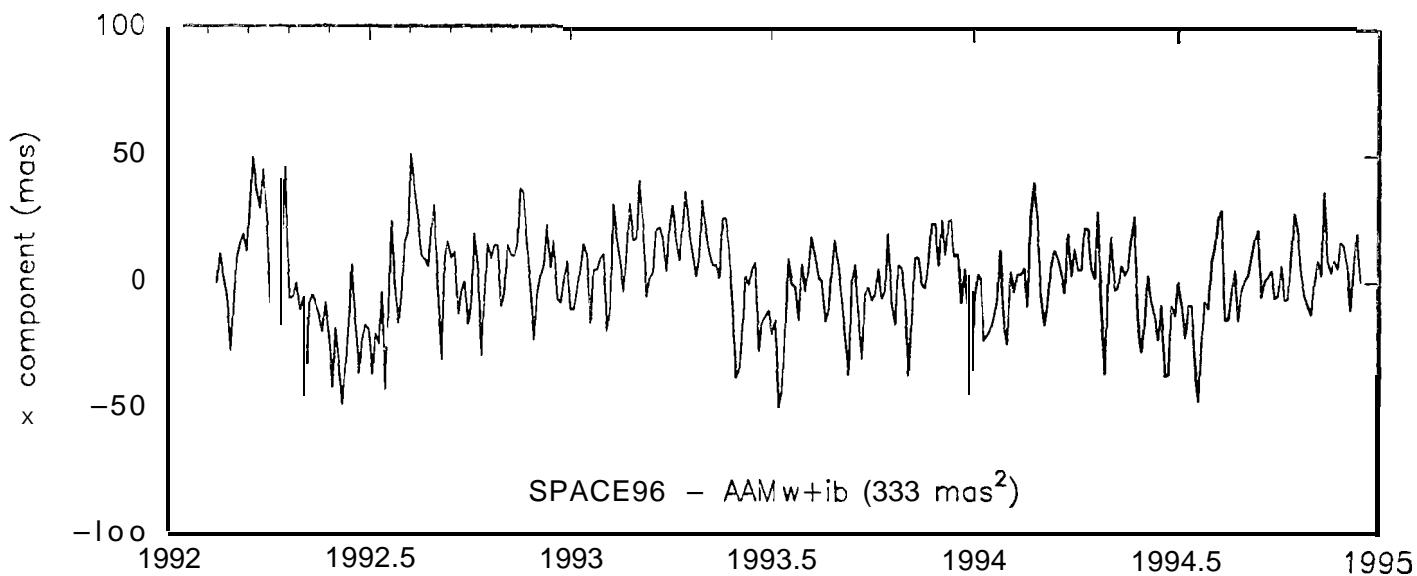
MOM AND M COM MOTION TRM



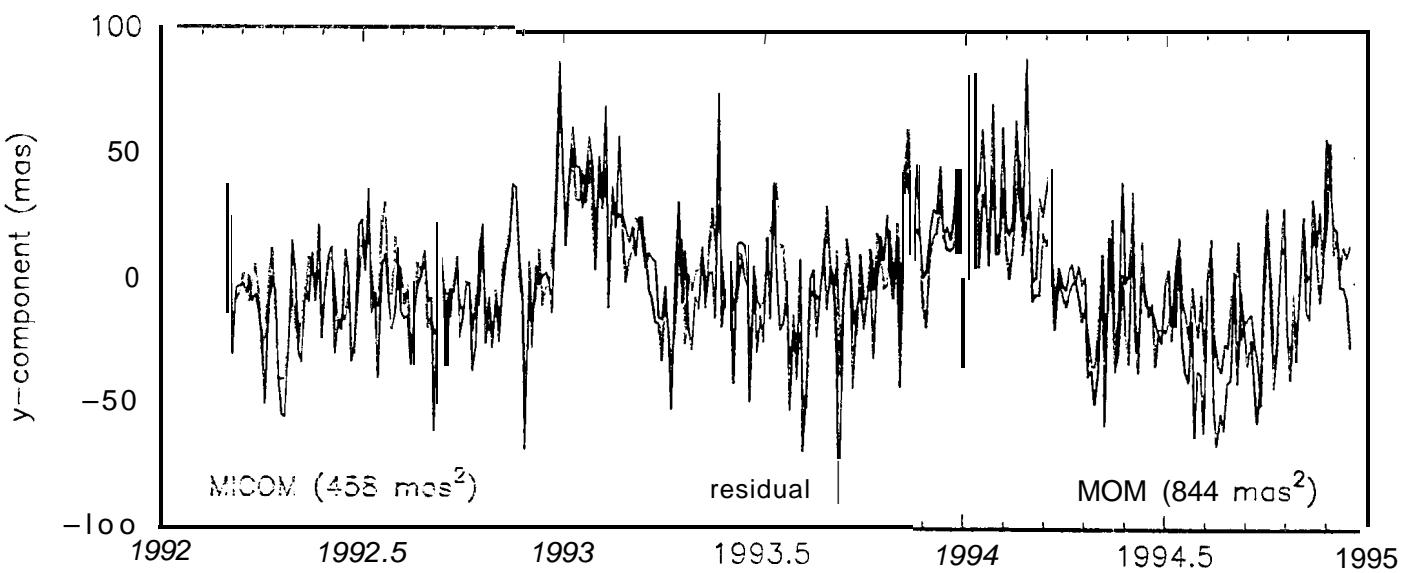
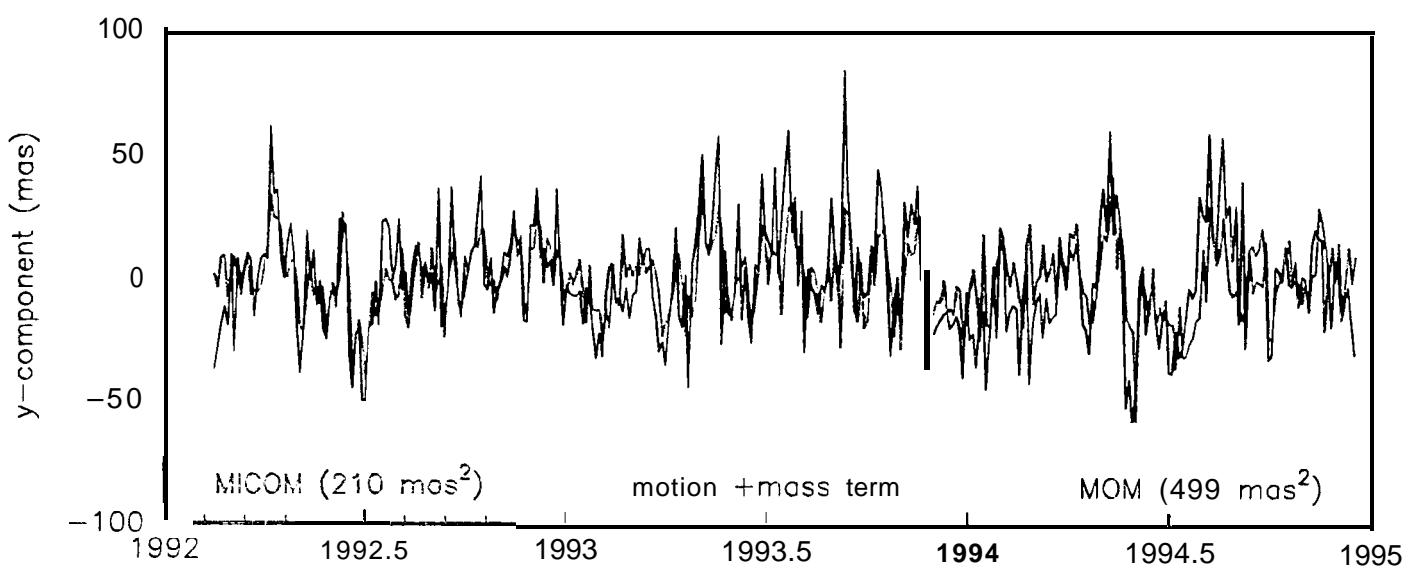
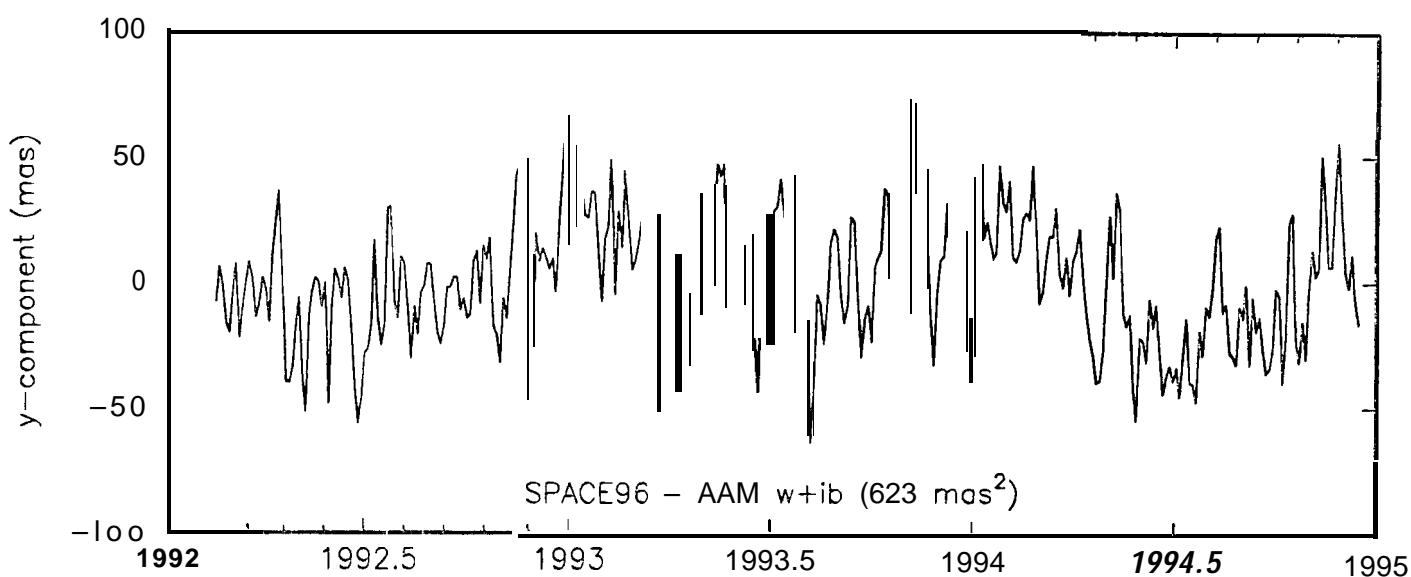
MOM AND MICOM MASS TERM



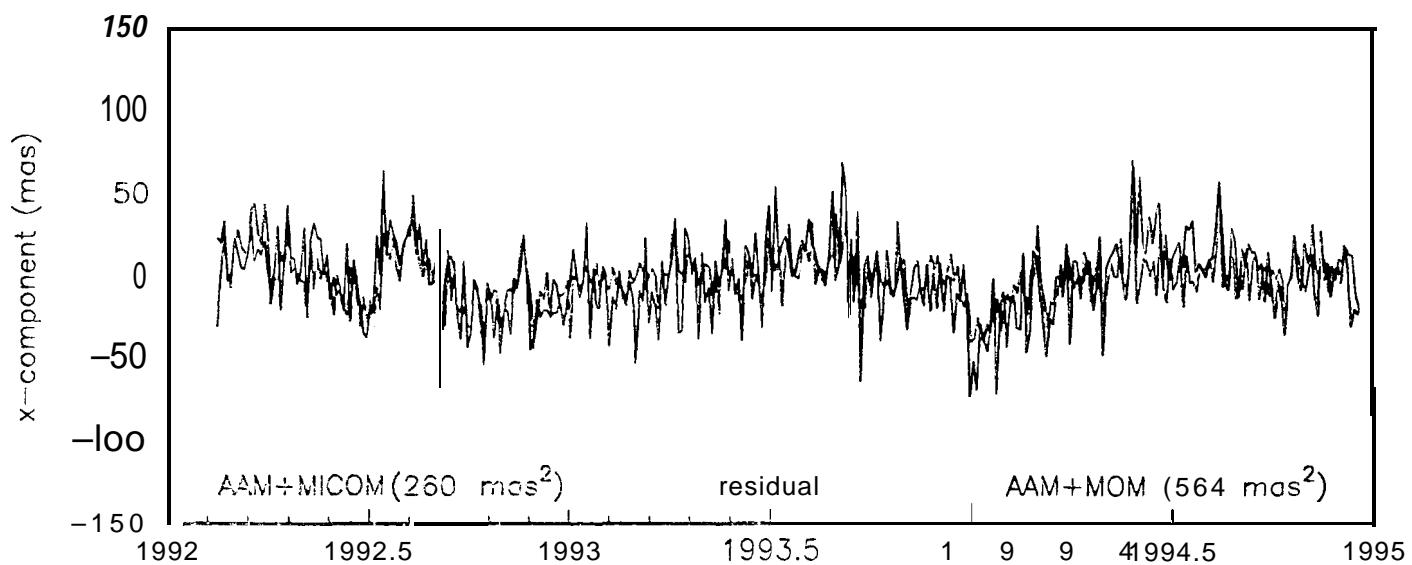
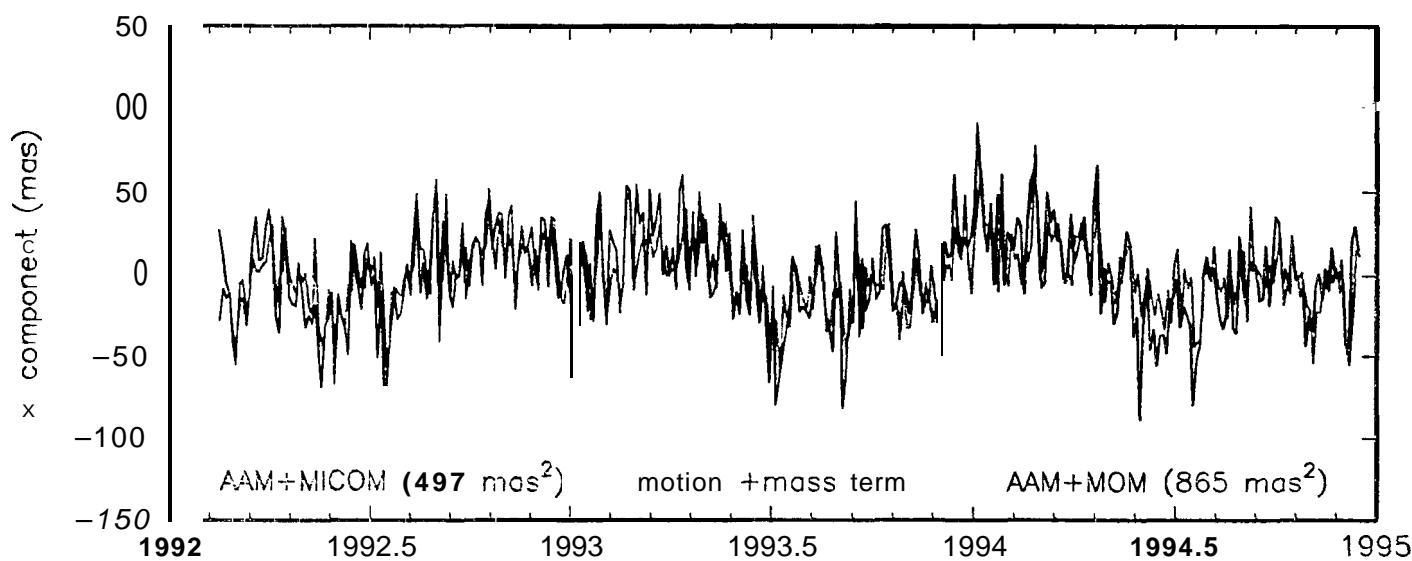
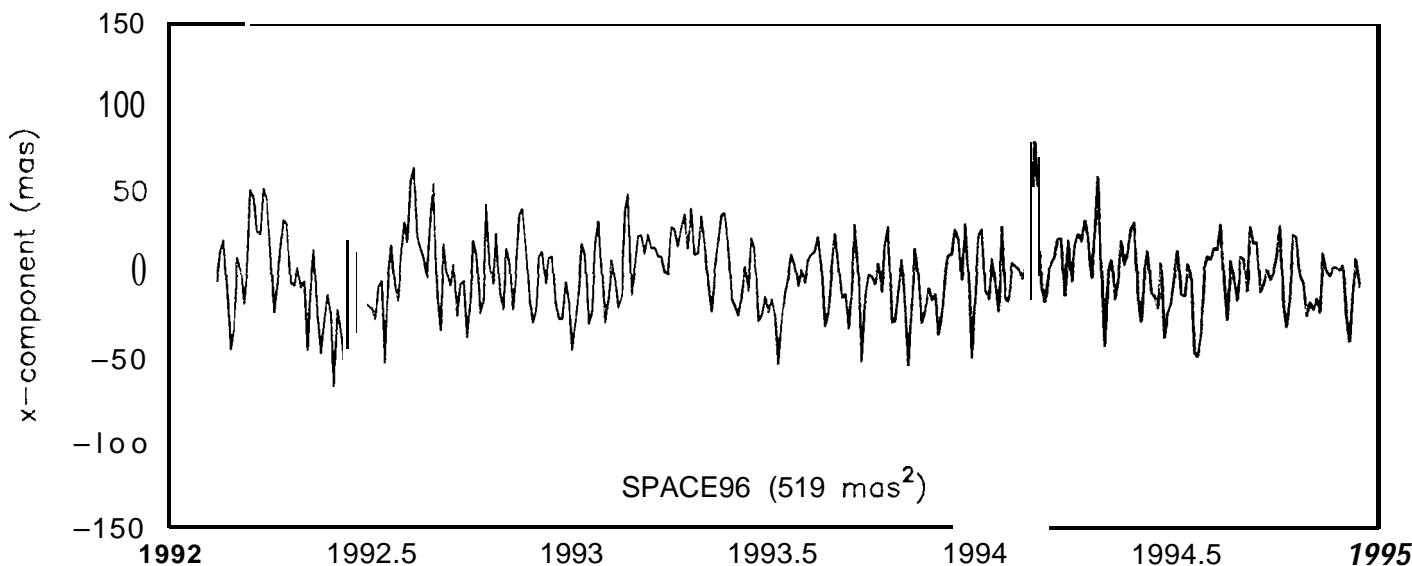
POLAR MO-I ION EXCITATIONSERIES



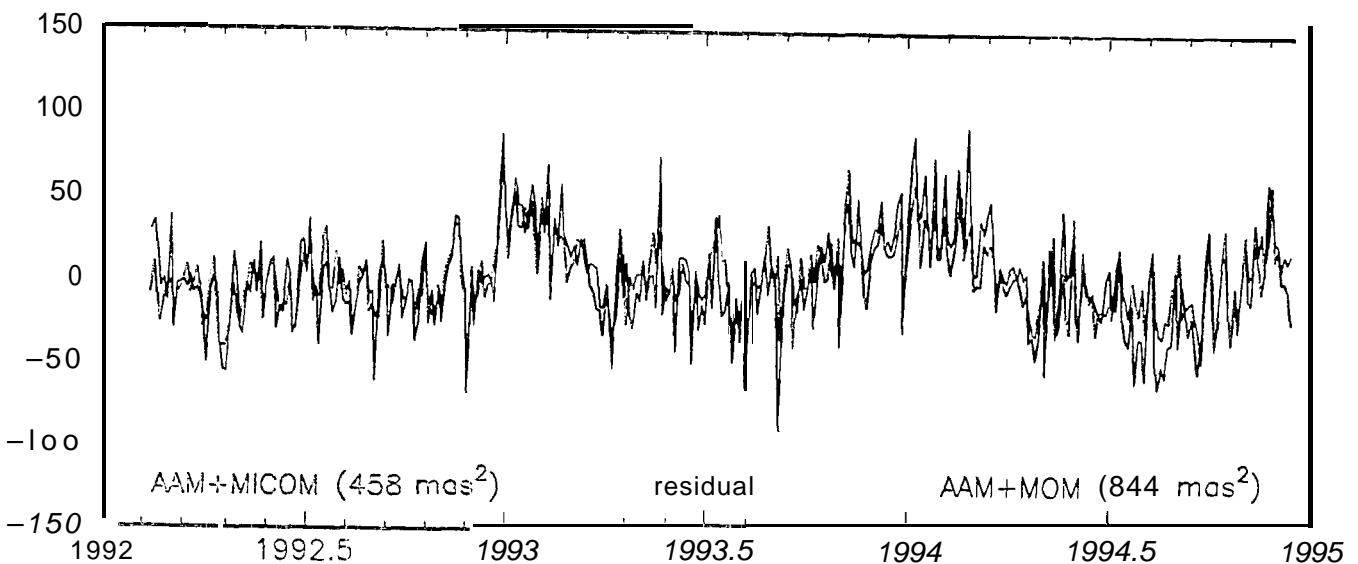
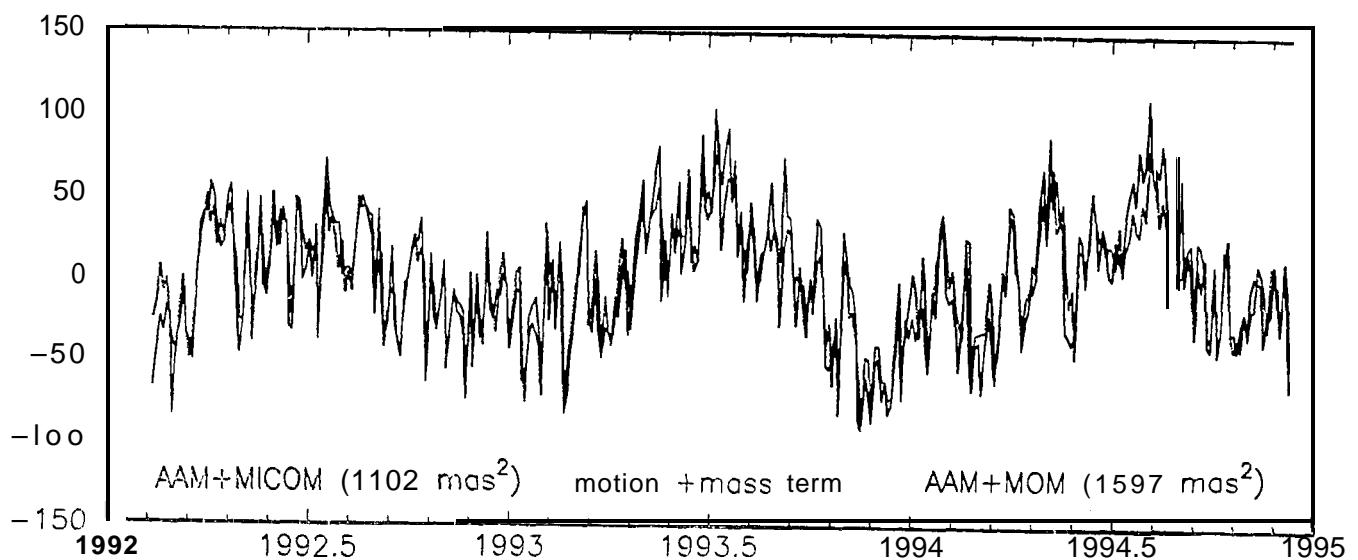
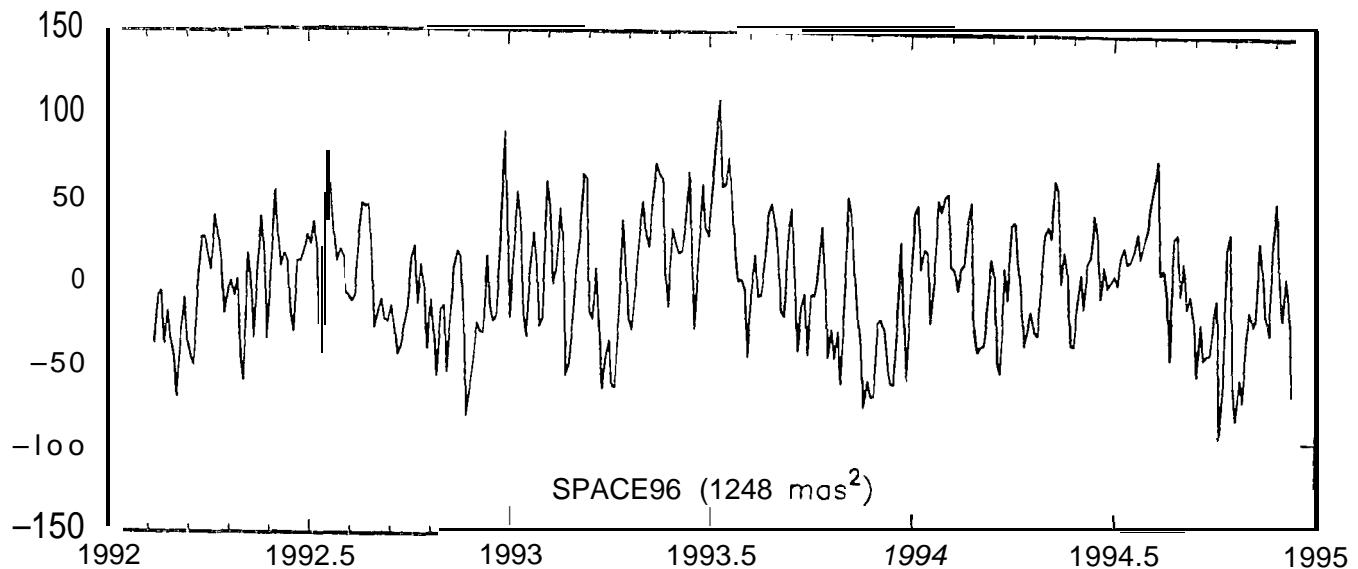
POLAR Me-IION EXCITATION SERIES



POLAR MOTION EXCITATION SERIES



POLAR MO-ION EXCITATIONSERIES



CORRELATION

BETWEEN SPACE96 & AAM/OAM SERIES

AAM / OAM series	PMX	PMY	CMPLX
AAM wind	0.46	0.55	0.50
AAM ib	0.36	0.65	0.59
MICOM current	0.26	0.13	0.23
MICOM height	0.52	0.31	0.39
AAM w+ib	0.59	0.71	0.69
MICOM c+h	0.48	0.30	0.37
AAM+MICOM	0.74	0.80	0.78

BETWEEN SPACE96-AAM RESIDUAL & OAM SERIES

OAM series	PMX	PMY	CMPLX
MICOM current	0.45	0.41	0.42
MICOM height	0.53	0.44	0.47
MICOM c+h	0.59	0.52	0.54

BETWEEN SPACE96-OAM RESIDUAL & AAM SERIES

AAM series	PMX	PMY	CMPLX
AAM wind	0.19	0.49	0.37
AAM ib	0.59	0.74	0.70
AAM w+ib	0.66	0.78	0.74

% VARIANCE EXPLAINED

OF SPACE96 BY AAM / OAM SERIES

AAM / OAM series	PMX	PMY	CMPLX
AAM wind	20.0	20.1	20.1
AAM ib	9.0	40.9	31.9
MICOM current	3.7	1.3	2.0
MICOM height	27.0	9.9	14.8
AAM w+ib	34.7	48.7	44.8
MICOM c+h	14.3	7.7	9.5
AAM+MICOM	50.0	62.4	58.8

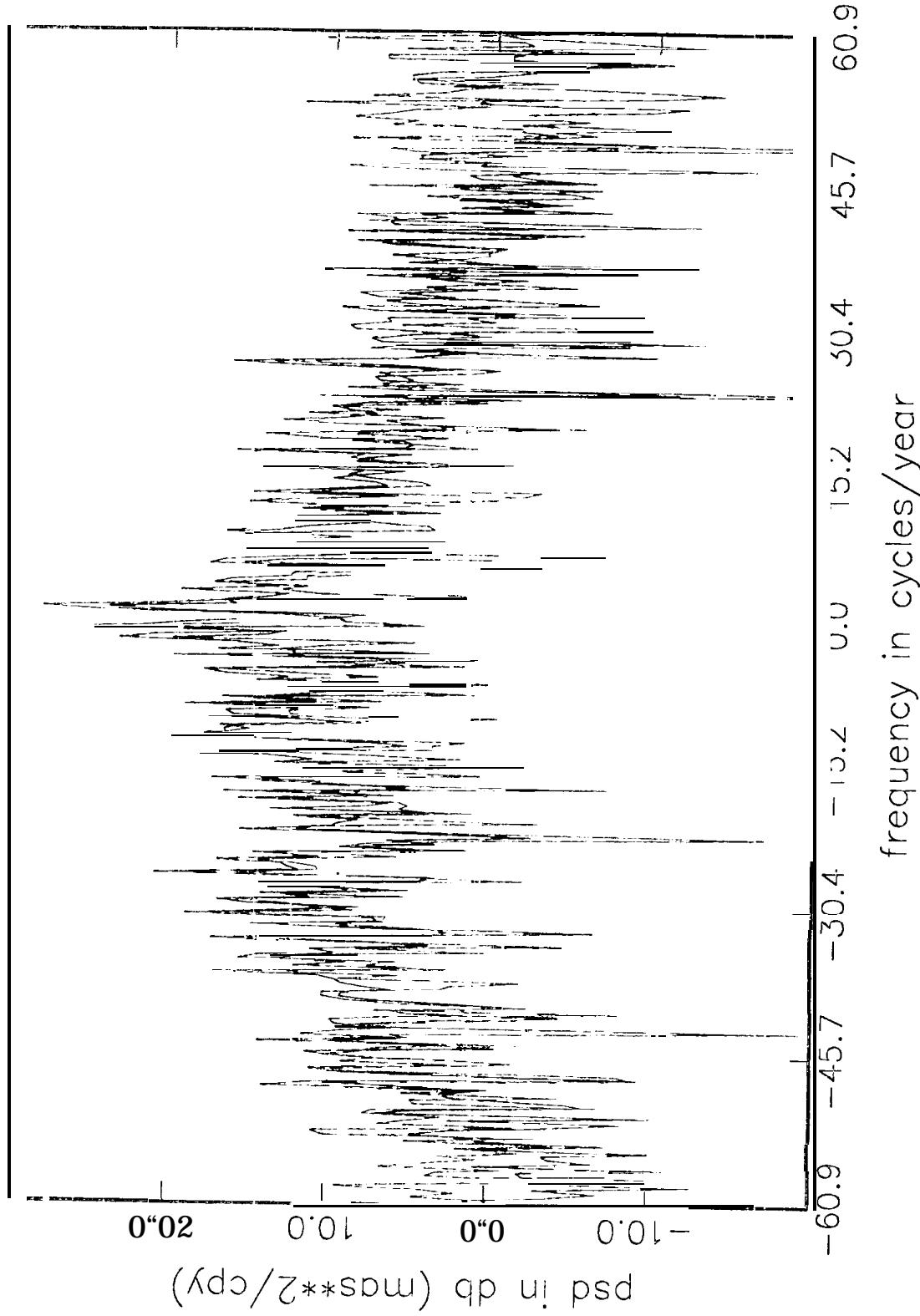
OF SPACE96-AAM RESIDUAL BY OAM SERIES

OAM series	PMX	PMY	CMPLX
MICOM current	19.8	14.8	16.5
MICOM height	27.9	19.1	22.2
MICOM c+h	21.9	26.5	24.9

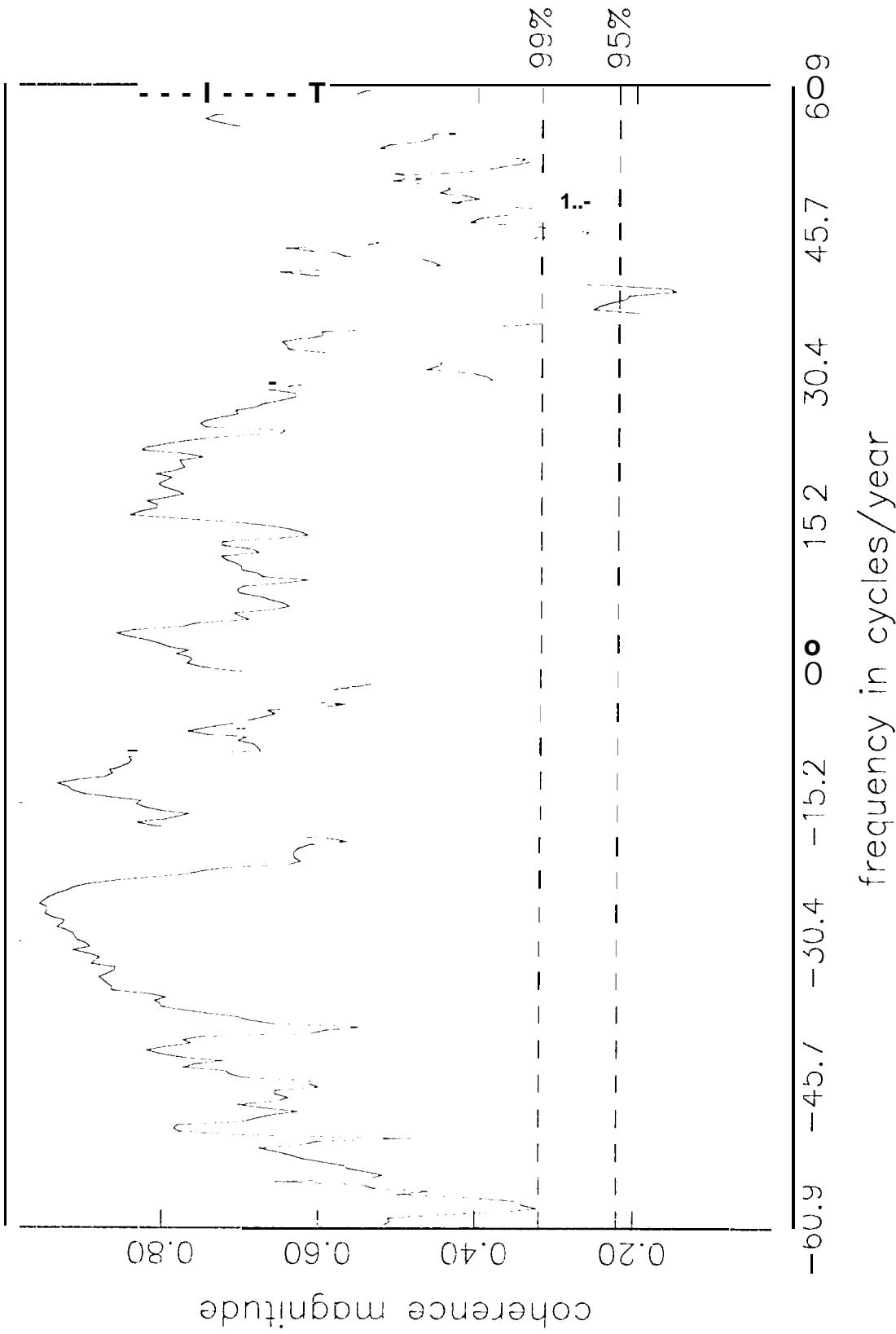
OF SPACE96-OAM RESIDUAL BY AAM SERIES

AAM series	PMX	PMY	CMPLX
AAM wind	0.1	17.6	12.9
AAM ib	35.0	54.7	49.3
AAM w+ib	41.7	59.2	54.5

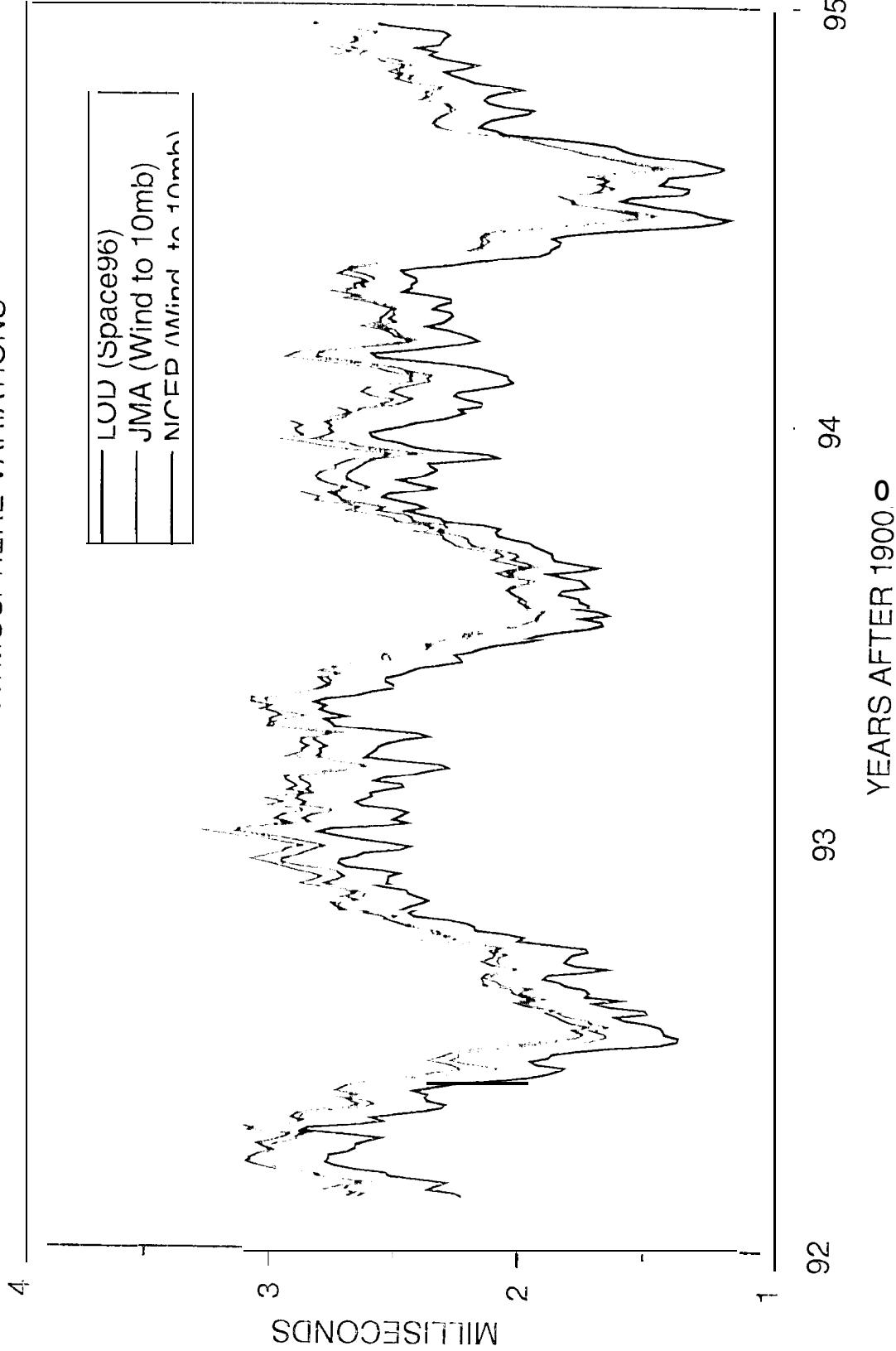
SPACE96 AND AAM+M COM SPECTRA



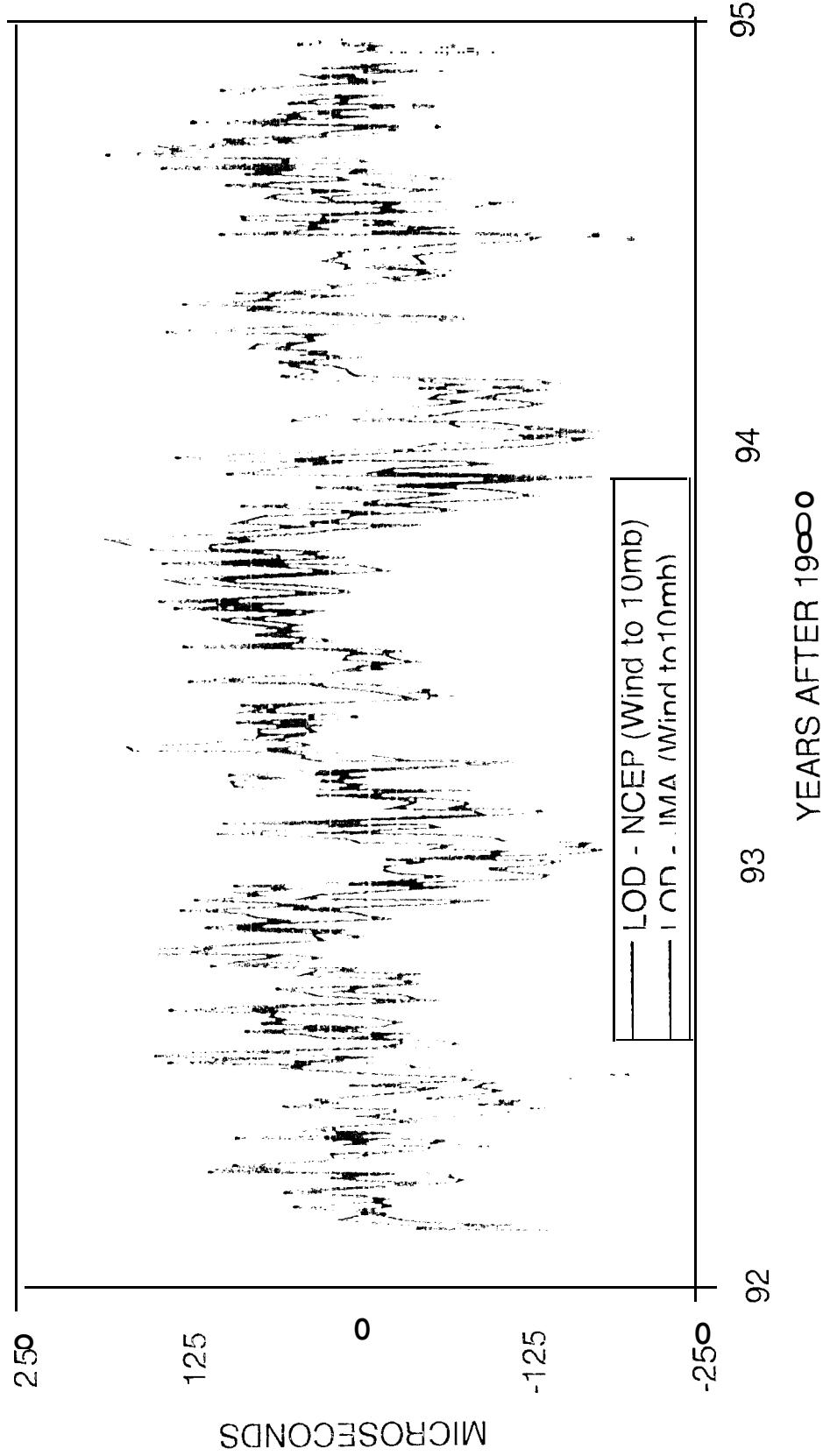
SPACE96 AND AAM+MICOM COHERENCE



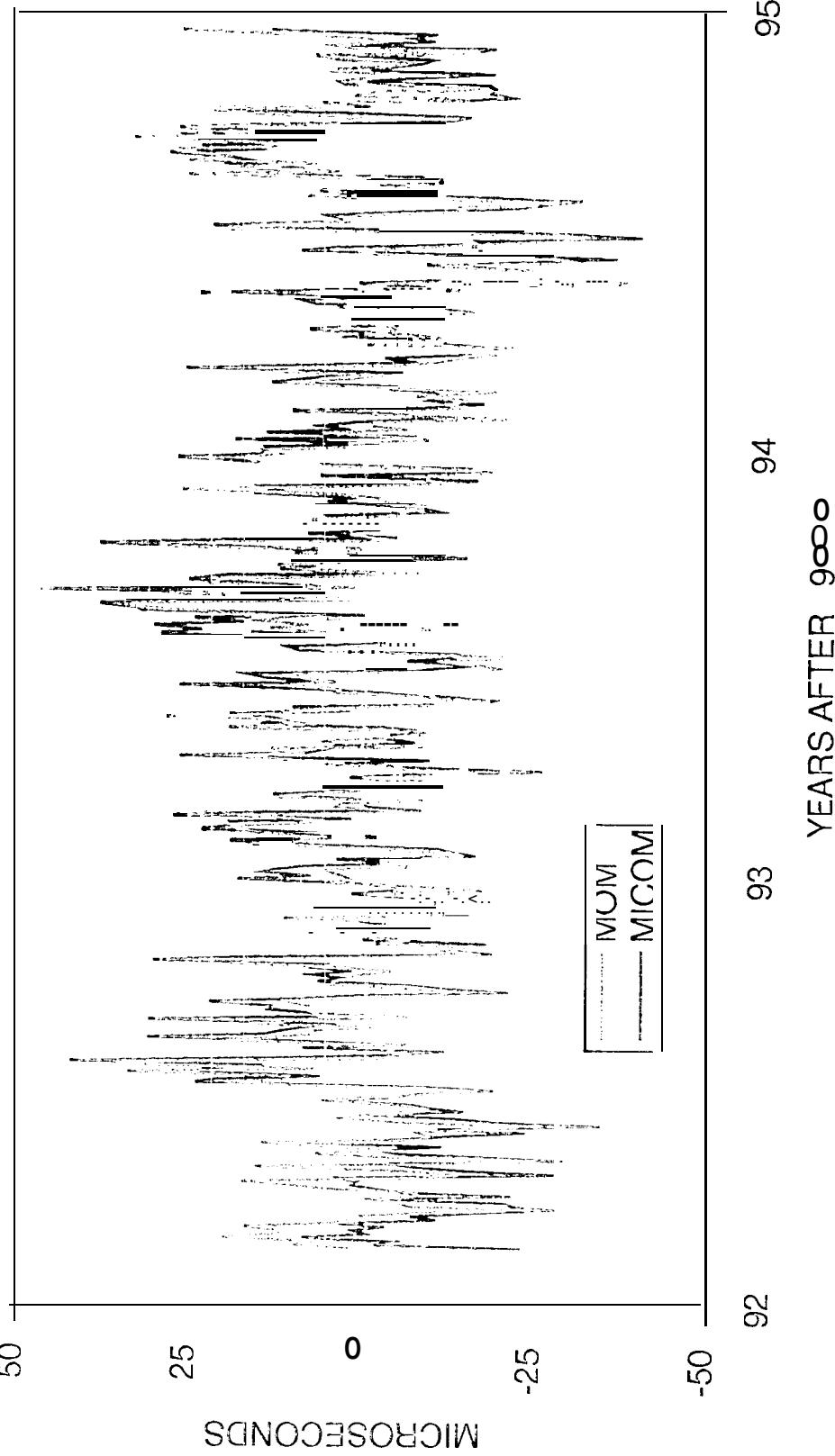
SOLID EARTH - ATMOSPHERE VARIATIONS

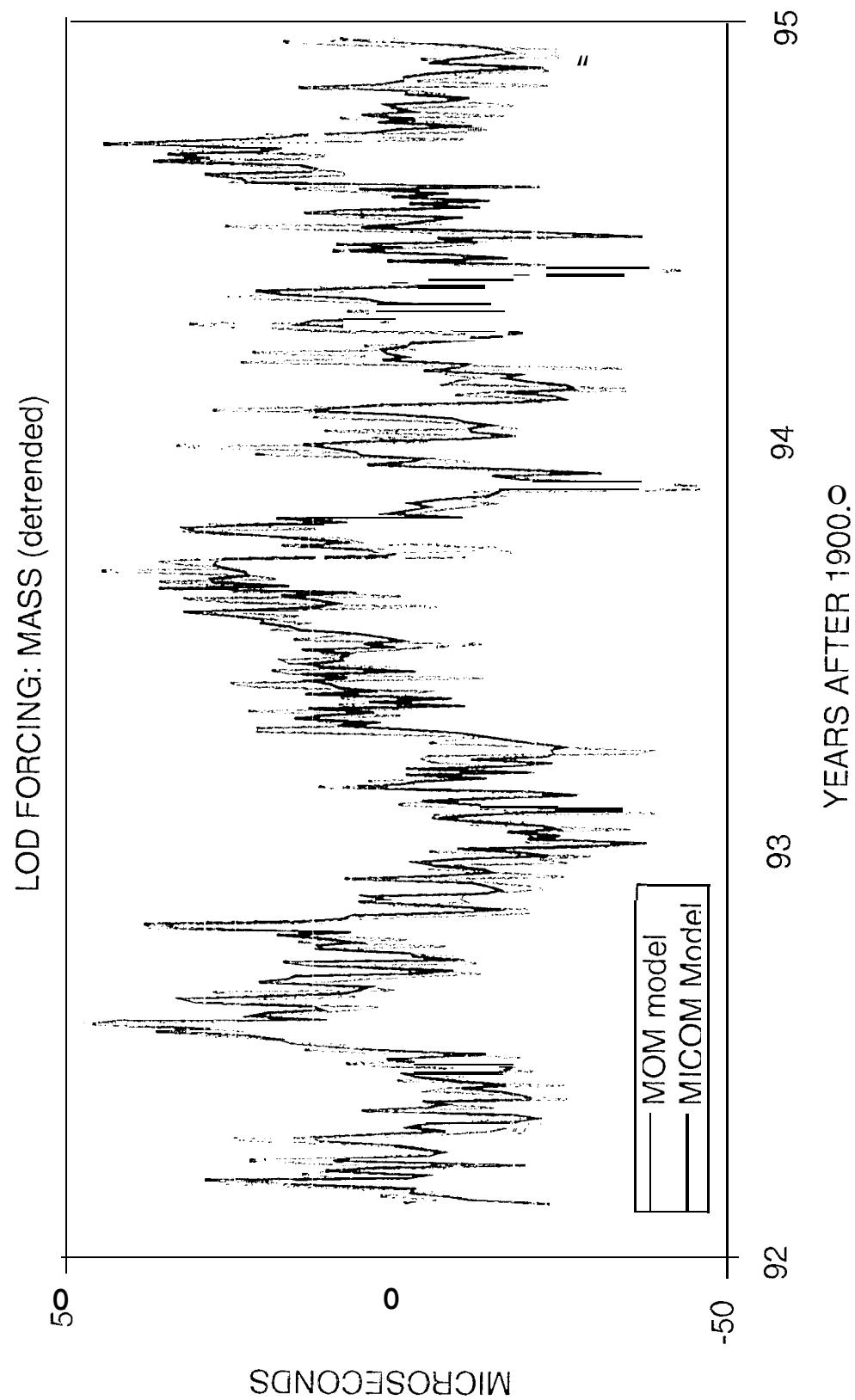


SOLID EARTH - ATMOSPHERE RESIDUAL (detrended)

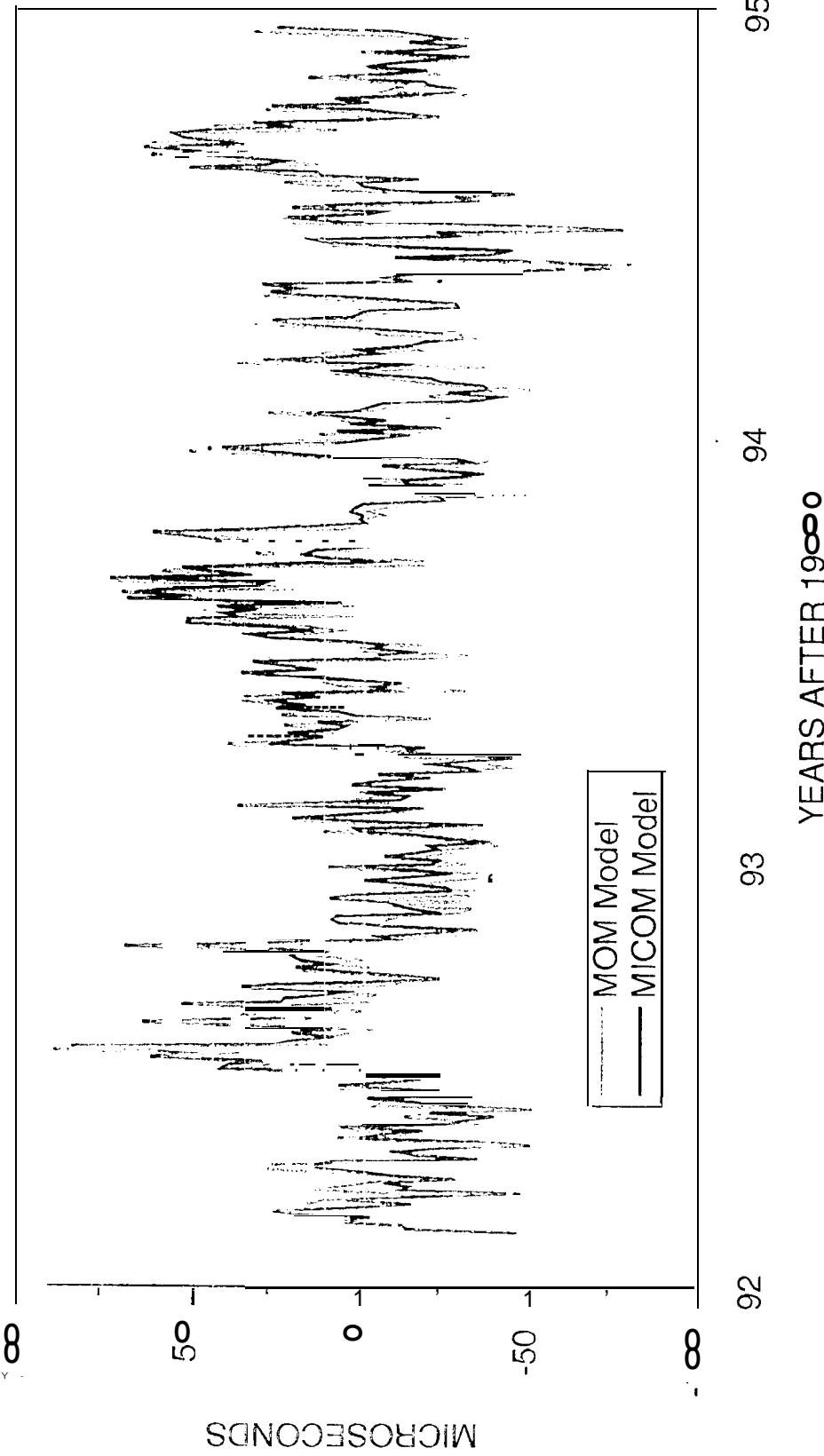


LOD FORCING: CURRENTS (detrended)

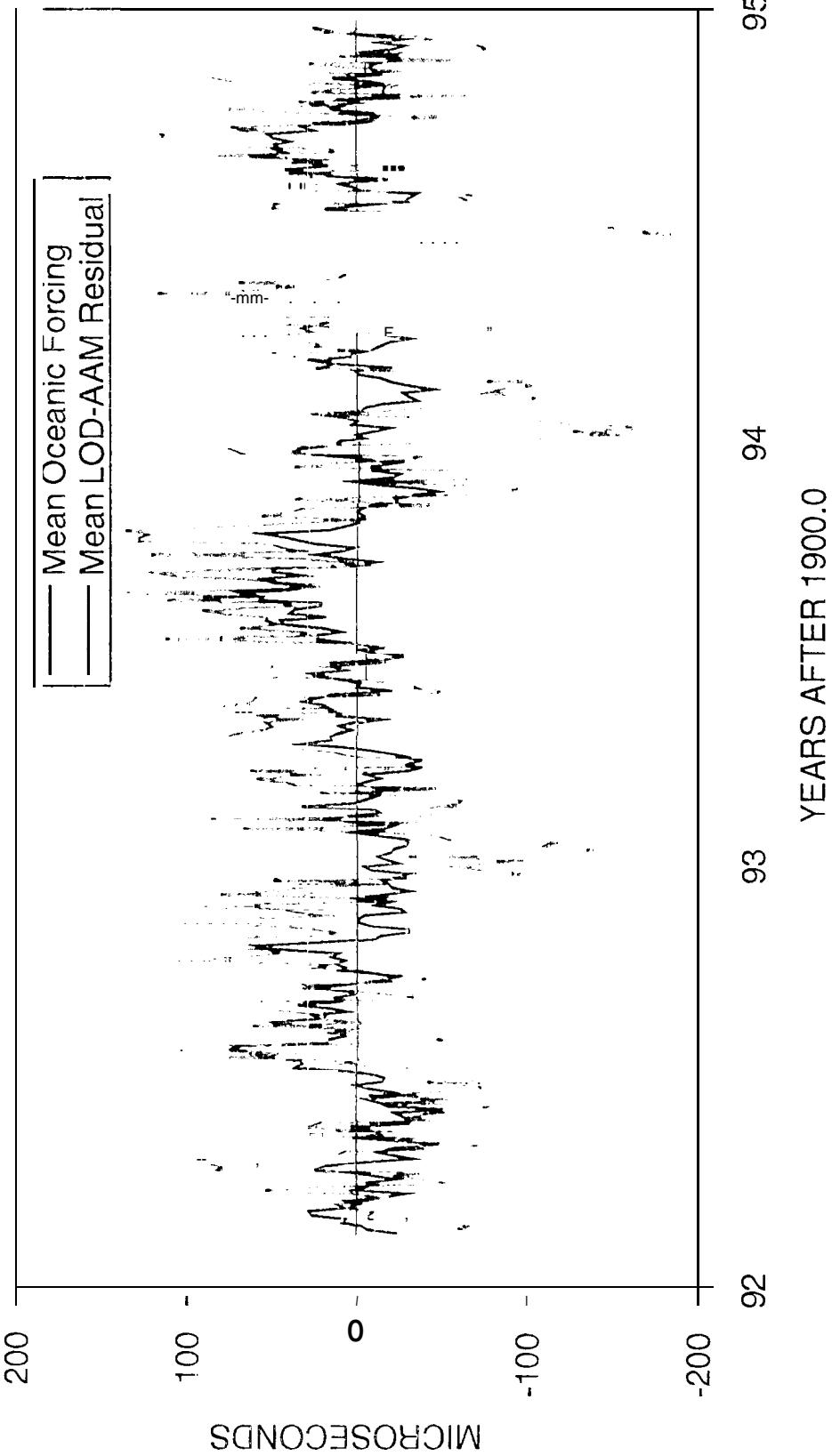




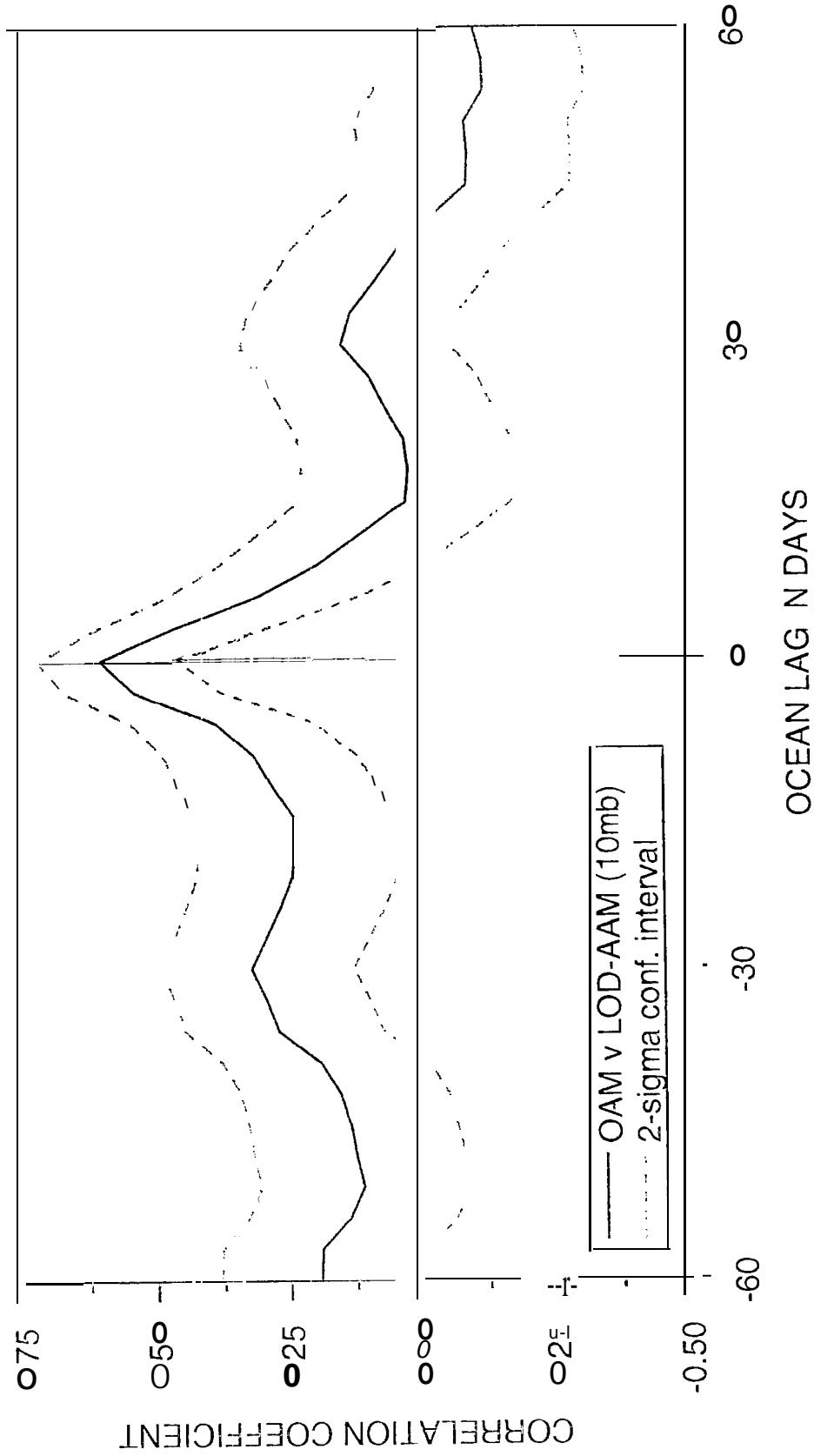
OCEANIC LOD FORC NG (detrended)



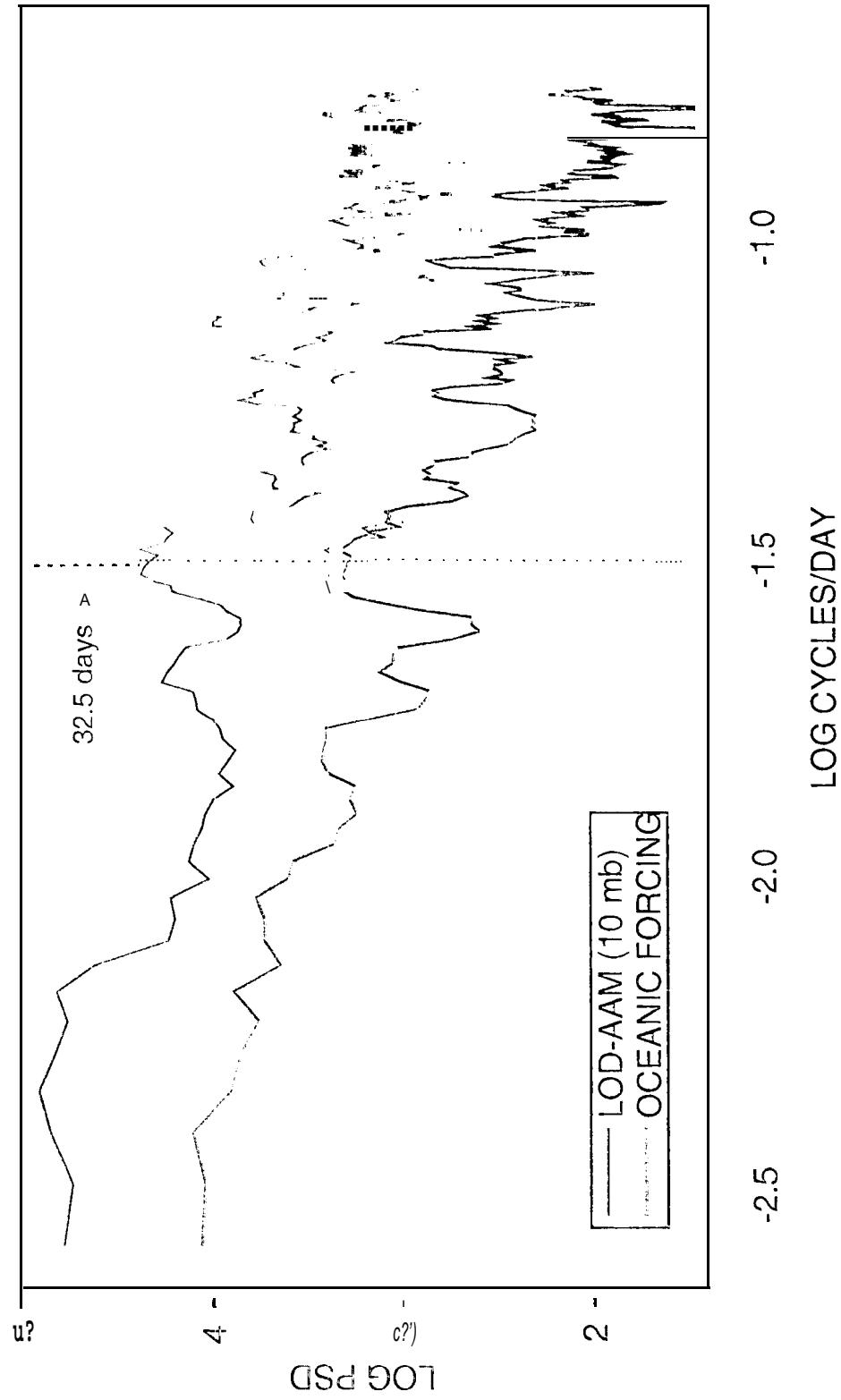
LOD RES DUAL vs OCEANIC FORC NG (detrended)



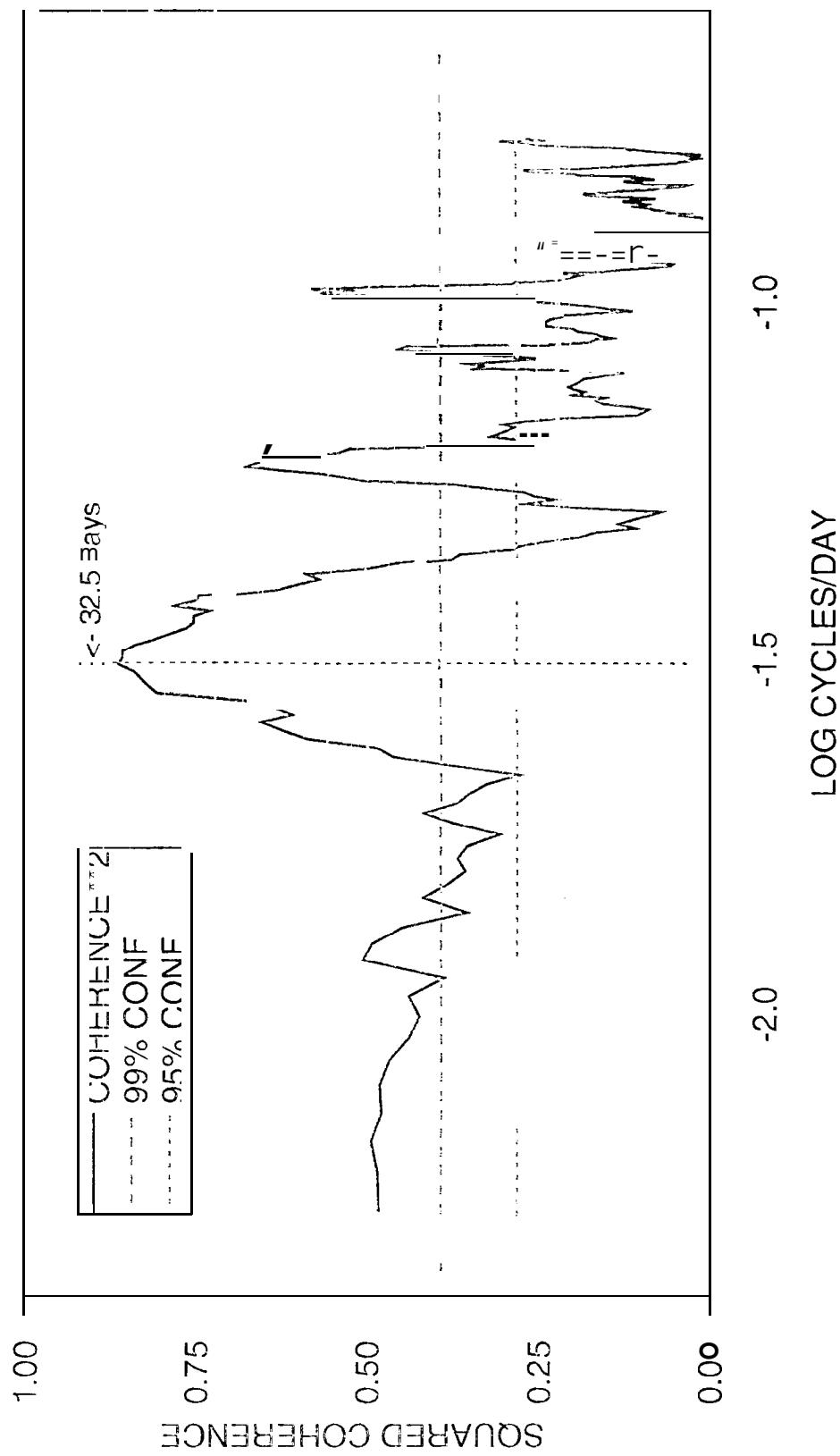
OCEAN v SOLID EARTH - ATMOSPHERE



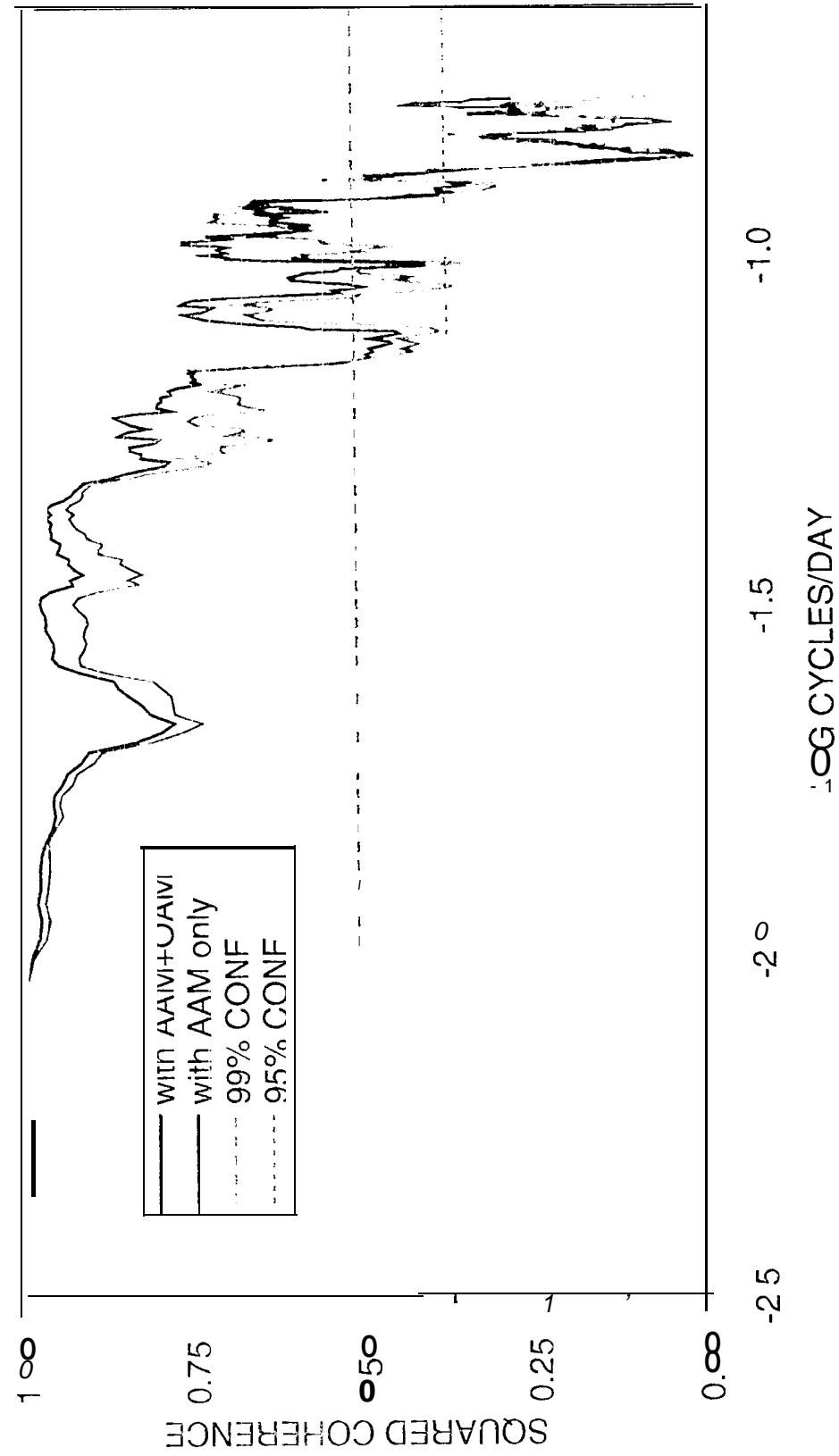
POWER SPECTRA



OCEAN FORCING v LOD-AAM



COHERENCE OF LOD:



Conclusions

By making proper allowance for climate and mass drifts, angular momentum variations produced by 2 substantially different OGCMs were shown to be very similar

- Both current and mass terms agree

Comparisons with geodetic and atmospheric data show that the model-simulated OAM series can significantly improve closure of the Earth's axial angular momentum budget

- Results enhance confidence in robustness of model simulations

High-quality geodetic measurements have the potential to serve as benchmarks for validating and improving complex geophysical models

- Benefits to both geodetic studies and ocean/atmosphere modeling

ACKNOWLEDGMENTS

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